Fisheries ecosystem model of the Chesapeake Bay: Methodology, parameterization and model exploration[1]

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1. Foreword (Lowell Bahner)

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2. Abstract

We describe an ecosystem model of the Chesapeake Bay prepared using the Ecopath with Ecosim approach and software. The construction has been carried out in close consultation with Chesapeake Bay researchers through a series of workshops. The model includes 45 functional groups and covers organisms at all trophic levels, but most detailed for the upper trophic levels. The data material primarily include assessment results from the area (including biomasses, mortality rates, catches, effort) supplemented with research vessel survey data (fisheries as well as biological oceanography studies), ecological studies as available from researchers and institutions in the region, as well as parameter estimates obtained from the literature where necessary to supplement local data.

Activities are underway to refine the temporal and spatial resolution of the ecosystem model as well as to continue to incorporate hydrographic data. In the meantime, emphasis is on understanding the relative roles played by fisheries and the environment in ecosystem changes over the last 50 years in the Bay.

The fisheries ecosystem model developed and refined as part of this endeavor is beginning to serve as a 'community' model. Many Bay-scientists have been involved in defining and constructing the model, and there are now several associated project activities. The purpose of this manuscript is to describe the data sources used to parameterize and "tune" the model. This documentation should to facilitate use and further development of this model, so that the Chesapeake Bay Fisheries Ecosystem Model can serve as a 'living' model. Future revisions

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to this model and documentation will be made available from the NOAA Chesapeake Bay Office website (www.chesapeakebay.net /ecosystem.htm).

3. Introduction

3.1. Chesapeake Bay

Chesapeake Bay, the largest estuary in the continental United States, is located midway along the Atlantic coast. In terms of surface area, here estimated to 10,000 km^2, (Derek Orner, personal communication) the Bay is divided between Maryland and Virginia, with the Virginia portion slightly exceeding the Maryland one (Figure 1). Physically, more than 20 major tributaries drain into the Bay from a watershed that stretches across six states – New York, Pennsylvania, Maryland, Delaware, Virginia and West Virginia, and the District of Columbia. The largest of these tributaries, the Susquehanna River, provides more than half of the fresh water that flows into the Bay. The Bay is a partially mixed estuary having an average tidal range of approximately 0.6 m (cited in 1989). Salinity within the Bay ranges from less than 0.5 ppt at its northern extreme to 32 ppt near the mouth. As such, the Bay can be divided into three major salinity regions, oligohaline (0-6 ppt), mesohaline (6-18 ppt), and polyhaline (>18 ppt). Water temperatures in the Bay vary greatly throughout the year, reaching 28-30 ºC in late summer and 1-4 ºC in late winter (Murphy *et al.*, 1997).

The mixture of freshwater from the tributaries and seawater from the coastal ocean creates and maintains a variety of brackish habitats within the Bay. Most notable are the marshes on intertidal lowlands, aquatic grass beds in the shallow flooded flatlands, and oyster reefs, which are a subtidal hard-bottom substrate (Murphy *et al.*, 1997). Due to such a diversity of

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habitats, the Bay is extremely rich in natural resources, supporting nearly 3,000 species of plants and animals within its waters and tidal margins. Most of the marine fishes that inhabit Chesapeake Bay spawn in the coastal ocean; however, some fish and crab species spawn in the lower portion of the Bay where salinity is very high. The net flow of seawater into the Bay and its tributaries serves to transport larval fishes and crabs to their nursery habitats. This transport mechanism is very important to the population dynamics of many species, since these nursery areas are highly productive and facilitate rapid growth under relatively protected conditions.

The diversity of habitats within Chesapeake Bay, combined with wide ranges of temperatures throughout the year, result in very dynamic seasonal changes in fish assembles and diversity. During late summer and early autumn, fish diversity reaches its maximum due to a movement of tropical species into the lower portion of the Bay. When the cooler temperatures of autumn arrive, most marine fish within the Bay begin to migrate either south to Cape Hatteras, NC or offshore to the edge of the continental shelf. During winter, the abundance and diversity of fish in the Bay is quite low. However, by early spring, abundance and diversity increase significantly as anadromous species enter the Bay, followed soon after by the warm-temperate and subtropical summer residents.

Since the early 1900s, production and seasonal dynamics of resources indigenous to Chesapeake Bay have supported a variety of commercial and recreational fisheries both within the Bay and along the Atlantic coast. During the past 50 years, sizable invertebrate fisheries in Chesapeake Bay were supported, including the eastern oyster (*Crassostrea virginica*), blue crab (*Callinectes sapidus*), soft clam (*Mya arenaria*), and hard clam

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(*Mercenaria mercenaria*). Large-scale finfish fisheries included striped bass (*Morone saxatilis*), American shad (*Alosa sapidissima*), river herring (*Alosa aestivalis*), white perch (*Morone americana*), bluefish (*Pomatomus saltatrix*), Atlantic menhaden (*Brevoortia tyrannus*), summer flounder (*Paralichyths dentatus*), weakfish (*Cynocision regalis*), Atlantic croaker (*Micropogonias undulates*), and spot (*Leiostomus xanthurus*). Several species have sustained significant harvest levels from these fisheries, and although trends in the commercial and recreational landings have been quite variable during the last several decades, many species have suffered over-exploitation. The prospect of over-fishing and the collapse of several Bay/coastal fish stocks during the 1900s prompted creation of several fisheries management agencies both along the Atlantic coast and within Chesapeake Bay. For coastal areas, the Atlantic States Marine Fisheries Commission (ASMFC) serves as a deliberative body, coordinating the conservation and management of shared near shore fisheries resources along the eastern seaboard from Maine to Florida (4.8 km or 3 miles off the coast), and the Mid-Atlantic States Fishery Management Council (MASFC) is responsible for managing fisheries in federal waters, which occur predominately off the mid-Atlantic coast (from 4.8 to 322 km, or from 3 to 200 miles offshore). Within the Bay, catch regulations and fisheries management plans for exploited resources are jurisdiction-specific, as determined by the Virginia Marine Resources Commission (VMRC), the Maryland Department of Natural Resources (MDNR), and the Potomac River Fisheries Commission (PRFC).

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3.2. *Multispecies management*

Traditionally, fisheries management plans have been based on various types of single-species analyses (e.g., stock assessments designed to derive estimates of population size and fishing mortality rates, synthesis of life history characteristics to determine fishing seasons, etc.). However, most single-species analyses do not explicitly consider the ecology of the species under management (e.g., habitat requirements, response to environmental change), ecological interactions among species (e.g., predation, competition) or technical interactions, (e.g., discards, bycatch), (NMFS, 1999; Link, 2002b; Link, 2002a). Basing fisheries management plans on both single-species characteristics and ecological processes is now strongly advocated (NMFS, 1999; NRC, 1999; Anon., 2004) and in some cases even mandated (NOAA, 1996).

The concept that ecological processes have the potential to strongly influence stock abundance is not novel to fisheries science. During the 1970s and 1980s, several single-species population models were extended to include multiple species and the implied ecological interactions (Andersen and Ursin, 1977; May *et al.*, 1979; Mercer, 1982; Kerr and Ryder, 1989; Daan and Sissenwine, 1991). These models fostered awareness of the importance and role of ecological processes on yield performances of fish stocks, but were generally viewed as underdeveloped. In recent years, however, this belief has changed significantly, largely due to the sophistication and increased number of multispecies assessment and ecosystem models (Hollowed *et al.*, 2000; Whipple *et al.*, 2000; Latour *et al.*, 2003). In many respects, it can be argued that the analytical development of these modeling approaches has reached the point where they can now yield management advice. However,

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there can be a penalty associated with the use of multispecies modeling approaches when compared to traditional single-species analyses, notably that more model parameters may need to be estimated which in turn creates the need for additional types of data.

In the Chesapeake Bay region fisheries management plans have been developed for numerous species, see Table 2 (Bonzek, 2004), and there has been a growing interest in ecosystem-based approaches to fisheries management, as evidenced by the recent development of fisheries steering groups. Effort dedicated to ecosystem-based management in the region include, 1) the ASMFC multispecies committee, 2) the convening of multispecies technical workshops (Miller *et al.*, 1996; Houde *et al.*, 1998), and 3) the goals for multispecies fisheries management set by the Chesapeake Bay 2000 (C2K) Agreement. In many respects, it can be argued that the multispecies fisheries guidelines in the newly released Fisheries Ecosystem Plan for the Chesapeake Bay and inherent to the C2K Agreement constitute the driving force behind this growing awareness and breaks new ground as the first fisheries ecosystem plan developed in the US.

The language of the C2K Agreement, as it pertains to multispecies fisheries management, reads as follows:

- By 2004, assess the effects of different population levels of filter feeders such as menhaden, oysters and clams on Bay water quality and habitat.

- By 2005, develop ecosystem-based multispecies management plans for targeted species.

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- By 2007, revise and implement existing fisheries management plans to incorporate ecological, social and economic considerations, multispecies fisheries management and ecosystem approaches.

In response to the C2K Agreement, the NOAA Chesapeake Bay Office, working through the Chesapeake Bay Stock Assessment Committee, initiated a project in October 2001 to develop an Ecopath with Ecosim (EwE) model of Chesapeake Bay. This report summarizes the results of the first years of development. Specifically, we present the 2004-version of the Chesapeake Bay EwE model, complete with detailed descriptions of the data used for model parameterization and calibration.

For many components of the model, accurate and precise data were not available to define key input parameters. Although many research activities designed to fill these data gaps have been initiated, several years of work are necessary before they become available. The current Chesapeake Bay EwE model should be considered work in process, and we expect it to evolve and improve in response to the collection of new information. Consequently, the current Technical Report should be considered descriptive of the 2004-version of the Chesapeake Bay Ecosystem Model. We expect the Technical Report to be under continuous development in the medium term and will make every effort to periodically release electronic versions of the report through the NOAA Chesapeake Bay office website (http://noaa.chesapeakebay.net).

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4. Methodology

4.1. The EwE ecosystem modeling approach

Ecopath with Ecosim (EwE) is a rather complicated and capable approach for ecosystem-based management of fisheries. Currently, the focus of EwE-based research is gradually shifting to addressing policy and conservation issues as part of the actual fisheries management process – notably in NMFS laboratories and regional US fisheries councils. EwE is now increasingly being used to address questions such as: What are the likely ecological, economical and social consequences of increasing effort for fine-meshed, bottom-trawl fisheries in a given area? What can we do to improve feeding conditions for Steller sea lion? What are the potential impacts and trade-offs of a proposed protected area?

The EwE software is the world's *de facto* standard for researching and evaluating options for ecosystem-based management of fisheries. There are more than 3000 registered users of the software representing 124 countries and over 200 hundred published applications. More than 30 graduate theses have been based on the approach, and more than half of all peer-reviewed ecosystem modeling publications in the Web of Science are based on EwE. EwE is developed at the UBC Fisheries Centre as open source, freely distributed software.

4.1.1. Ecopath

The development of an Ecopath model can be traced back to early work on the ecosystem dynamics of a coral reef in Hawaii (Polovina, 1984). An Ecopath model uses trophically linked biomass pools to create a mass-balanced snapshot of the resources and interactions in an ecosystem (Christensen and Pauly, 1992; Pauly *et al.*, 2000; Christensen and Walters,

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2004). The biomass pools typically represent either a single species or a group of species that comprise an ecological guild. They can also be split into ontogenetic age or size categories (juvenile, sub-adult, adult, etc.), commonly called 'stanzas', if desired. Biomass pools are created for all major components of the ecosystem regardless of trophic level.

The parameterization of an Ecopath model is based on satisfying two 'master' equations. The first equation describes the how the production term for each group can be divided for an arbitrary time period:

> production = catch + predation + net migration + biomass accumulation + other mortality. (1)

More formally, equation (1) can be expressed as:

$$B_i (P/B)_i EE_i = Y_i + E_i + BA_i + \sum_{j=1}^{n} B_j (Q/B)_j DC_{ji} \quad (2)$$

where for biomass pool $i = 1, \ldots, n$, B_i is total biomass during the period of question; $(P/B)_i$ is the production to biomass ratio; EE_i is the ecotrophic efficiency, defined as the fraction of the production that is consumed within or harvested from the system; Y_i is the yield or catch in weight (note that $Y_i = F_i B_i$ where F is the fishing mortality rate); E_i the net migration rate (emigration – immigration); BA_i is the biomass accumulation rate for (i); B_j is the biomass of the consumers or predators of (i); $(Q/B)_j$ is the food consumption per unit biomass for consumer j; and DC_{ji} is the average fraction of i in the diet of j (note that $DC_{ji} = 0$ when j does not eat i).

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At a minimum, Ecopath requires input on DC_{ji}, Y_i, and three of the following four parameters for each species or biomass pool in the model: B_i, $(P/B)_i$, $(Q/B)_i$, and EE_i (mass balance principles are used to estimate the fourth parameter). If all four parameters are known, then Ecopath can be used to estimate either BA_i or E_i. Equation (2) implies that ecosystem under study is described completely by an n-dimensional system of linear equations, the solutions of which can be easily calculated (Mackay, 1981) and the resulting estimates of biomass, production, and consumption can be used to construct a quantitative network diagram of energy flow for the system (Ulanowicz, 1986).

The second 'master' equation is based on the principle of conservation of matter within a group and is designed to balance the energy flows of a biomass pool:

$$\text{consumption} = \text{production} + \text{respiration} + \text{unassimilated food} \qquad (3)$$

Winberg (1956) defined consumption as the sum of somatic and gonadal growth, metabolic costs, and waste products. Equation (3) generally follows this definition, but differs in the sense that it is used to estimate losses rather than to measure growth. Balance of the energy equation is achieved by estimating respiration from the difference between the consumption, production, and unassimilated food terms. For more details on Ecopath, see Christensen and Pauly (1992) and Christensen and Walters (2004).

4.1.2. Ecosim

Ecopath is used to describe the interactions among resources within an ecosystem, while it relies on additional modules to simulate the dynamics of the ecosystem resources and the effects of different management strategies on the structure and function of an ecosystem.

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The time-dynamic module, denoted Ecosim, provides a simulation capability that facilitates policy exploration at the ecosystem level, with initial parameters inherited from the base Ecopath model. To construct an Ecosim model, it is necessary to re-express the system of linear equations in (2) as a system of coupled differential equations. This transformation takes the form (Walters *et al.*, 1997; Walters *et al.*, 2000; Christensen and Walters, 2004):

$$\frac{dB_i}{dt} = g_i \sum_{j=1}^{n} c_{ji} - \sum_{j=1}^{n} c_{ij} + I_i - (M_i + F_i + e_i) B_i \quad (4)$$

where g_i is growth efficiency; F_i is the instantaneous rate of fishing mortality; e_i is the rate of emigration; I_i is the rate of immigration; and c_{ij} (c_{ji}) is the consumption of biomass pool *i* (*j*) by biomass pool *j* (*i*). This system of equations is used to represent the spatially aggregated dynamics of entire ecosystems and is combined with explicit age/size-structured delay-difference equations to represent populations that have complex life histories and selective harvesting of older animals. An important aspect of Ecosim is the expression of the consumption or 'flow' rates among linked species or biomass pools. Consumption of prey *i* by predator *j* is modeled as:

$$Q_{ij}(B_i, B_j) = \frac{a_{ij} v_{ij} B_i B_j}{(2v_{ij} + a_{ij} B_j)}, \quad (5)$$

where a_{ij} is the rate of effective search for prey *i* by predator *j* and v_{ij} is the behavioral exchange rate between vulnerable and invulnerable prey pools (Figure 2). Equation (5) is based on the notion that consumption is limited by 'risk management' behaviors of predators and prey at very small time scales. That is, predator-prey interactions are assumed to take place primarily in restricted 'foraging arenas' where prey only become vulnerable to predation through their own requirements for resource acquisition (Walters *et al.*, 1997; Walters *et al.*, 2000).

Relative to Ecopath, Ecosim introduces a number of new parameters, the most sensitive of which appear to be the vulnerabilities (Christensen and Walters, 2004). The vulnerability parameter expresses how much the predation mortality for a given prey can increase if the predator abundance is increased. When the predator is close to its carrying capacity with regard to the given prey, the predation mortality cannot be increased any further (v=1), and an increase in predator abundance, (e.g., due to good recruitment) will be compensated for by a decrease in predator consumption rates. This in turn will result in lower predator production, and the predator abundance will move back toward its carrying capacity. In an opposite response, a decline in population size, for a predator close to its carrying capacity, will be compensated for by a comparative increase in average consumption rates, which will bring the predator back toward its carrying capacity. A population at its carrying capacity is a stable population.

On the other hand, if the predator is far from its carrying capacity for a given prey the situation is very different. An increase in predator biomass will lead to an increase in prey mortality rate. In Ecosim terminology, the vulnerability parameter for the prey will be high. The consumption rate of the predator will remain relatively constant, and the increase in its biomass will manifest itself in population growth. There will be only limited compensation.

Turn the situation around in these examples and the result is that a decline in biomass for a predator close to its carrying capacity will be compensated for: surplus production will lead to improved individual conditions, and the predator population will move back toward its

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carrying capacity. However, when a predator population is far from carrying capacity, a decline in its biomass will result in little compensation, for prey is much less of a limiting factor, and the population decline will continue. The crucial aspect for vulnerabilities is thus to consider how far a given predator is from its carrying capacity with regard to a given prey.

In general, it is not possible to estimate vulnerabilities from field or laboratory data. However, to assist with identifying appropriate vulnerabilities, Ecosim includes several methods of estimation (see Christensen *et al.*, 2004 for details on these methods), and it is recommended that vulnerabilities be estimated based on time-series analyses, i.e. by evaluating ecosystem behavior over time.

Lastly, time series data for model calibration is essential for developing and validating an Ecosim model. Therefore, time series data depicting trends in relative and absolute biomass, fishing effort by gear type, fishing and total mortality rates, and catches for as long a period as possible should be viewed as additional data requirements.

4.1.3. Nutrient loading

At the conception of the Chesapeake Bay EwE project, EwE did not have the ability to account for physical and chemical factors as a part of the ecosystem being modeled. However, recent developments in the Ecospace component of the EwE modeling approach have helped alleviate this shortcoming. Working with a model linked to Ecospace for Florida Bay and for Tampa Bay, time series of salinity, nutrients and oxygen concentrations have been successfully emulated, both seasonally and inter-annually (Walters *et al.*, unpublished results). Such chemical and physical data time series, with high spatial and temporal resolution, are available for the Chesapeake Bay as well, and we have modified the Florida model for use in Chesapeake Bay.

The model includes three sub-models, all working with monthly time steps; 1) a physical model computing current speed and direction for surface and deep layers; 2) a static chemistry model estimating concentration of phosphorous, salt, phytoplankton and suspended particulates; and 3) a dynamic ecological model simulating growth and mortality of sea grass and epiphytic algae.

We have made use of historical information on nutrient loading and physical mixing to calculate changes in primary production in Chesapeake Bay using this model. From the model, we derived monthly nutrient-loading factors that are used to drive the fitted Ecosim model. The model and the data material are presented in Appendix B, C and D.

The hydrodynamic model requires time series data on wind vectors and gauge data from major freshwater inputs as well as bathymetry and some basic water chemistry information that is routinely collected in biological oceanography studies. Model outputs include a time series of total primary production, nitrogen and phosphorous concentrations, oxygen and salinity, which we have compared to historical data to aid in model parameterization. In addition, a sea grass sub model predicts total biomass and the spatial distribution of sea grasses in response to changes in water chemistry and light penetration. A historical reconstruction of sea grass communities in the Chesapeake Bay area will serve to test hypotheses about how changes in sea grass beds have affected biota that are associated/dependent on sea grasses, on both spatial and temporal scales; this work remains to be done.

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4.1.4. Addressing uncertainty

The EwE model presently incorporates several approaches for explicitly addressing uncertainty. We note:

- A 'pedigree' routine for characterizing the origin of input data and for developing an overall index of model quality;
- The Ecoranger routine for explicit consideration, in a Bayesian context, of the uncertainty inherent in all input and it's impact on estimated parameters;
- A formal sensitivity analysis for documenting the effect of inputs on estimated parameters;
- A Monte Carlo routine that can be used in the time-dynamic module to evaluate the effect of parameter uncertainty on policy questions;

Uncertainty in the model is documented and considered both during the building of the Ecopath model and as part of the Ecosim simulations. Each data entry cell in the Ecopath spreadsheets has been assigned a 'pedigree' or coded statement categorizing the origin of a given input, (i.e., the type of data on which it is based), and similarly specifying the likely uncertainty associated with the input. For example, data on biomass derived from biomass surveys from the area local to the model are given a higher pedigree value (less associated uncertainty) than if predicted by models based on catch per unit effort (CPUE) data. The overall pedigree of the model is calculated during the balancing process, giving an indication of the 'quality' of the model.

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4.2. Age-structured single-species assessment model

A necessary requirement for the EwE reconstruction approach is to provide at least one (more is preferable) biomass input into Ecopath as well as historical information on the removals or fishing mortality rates. This is a key requirement for modeling the known historical disturbances in Chesapeake Bay. This information is obtainable from single-species assessment models and in cases were model groups are partitioned into multiple life-history stanzas, an age-structured model is preferable such that fishing mortality rates for each stanza (if applicable, e.g., certain fishing gears harvest a specific stanza) can be calculated from the estimated age-composition. Typical statistical catch-at-age models are notorious for having hundreds and sometimes thousands of parameters, this "overparamterization" is not necessary (Walters and Martell, 2004). In many of the assessments here, we lacked sufficient information to carry-out such comprehensive and detailed assessments and opted for a much simpler approach. In this section we briefly describe the derivation of an age-structured assessment model parameterized from two leading (unknown) parameters that, in essence, are equivalent to the maximum intrinsic rate of growth and the carrying capacity of a simple surplus production model. In short, these two leading parameters represent the long-term unfished biomass (Bo) and the maximum juvenile survival rate or recruitment compensation. Of utmost importance is the estimation of the long-term unfished biomass. For this, we rely heavily on meta-analytical results of Myers *et al.* (1999) to provide prior information for recruitment compensation at low spawning abundance. This is especially important in cases where relative abundance indices lack sufficient contrast to estimate both parameters.

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For bluefish and several other species, an age-structured assessment model was used to reconstruct historical biomass and a time series of fishing mortality rates, which were used to force Ecosim simulations. Input data for the assessment model include: growth information (von Bertalanffy growth parameters), length-weight relationships (i.e., $w_a = aL^b$), parameters for a maturity cumulative frequency curve to calculate spawning stock biomass, natural mortality rate estimates, and parameters that describe size selectivity. Model parameters were estimated by fitting the model to abundance data as well as to catch rate information. Each of the abundance indices was assumed to be proportional to stock size, and observation errors were assumed to be lognormal. The age-structured population model includes a Beverton-Holt type stock recruitment function and the model was parameterized using a leading parameter setup, where the population scale (or capacity) was determined by R_o (the equilibrium unfished recruits) and the maximum rate of population change was defined by a recruitment compensation parameter (k). In most cases only observation errors were assumed.

4.2.1. Equilibrium Conditions

Beginning with the Beverton-Holt recruitment model:

$$R_e = \frac{\alpha E_o}{1 + \beta E_o} \tag{6}$$

the two parameters (α and β) can be derived given initial estimates of R_o, M and k. The maximum survival rate (α) is simply a multiple of number of recruits produced per unit of egg production, or:

$$\alpha = K \frac{R_o}{E_o} \tag{7}$$

and the asymptote of the recruitment function is defined by:

$$\beta = \left[\frac{\alpha E_o}{R_o} - 1 \right] \Big/ E_o \tag{8}$$

The equilibrium egg production (E_o) is simply the product of the equilibrium recruits and the number of eggs produced per recruit. The number of eggs per recruit (ϕ_e) is just the product of survivorship to age a times mean fecundity of age a individuals. It is not necessary to know the exact fecundity of any specific age group, but rather the relative differences in fecundity between separate age classes. Here we assume that egg production is proportional to body weight and the equilibrium egg production (E_o) for a population at equilibrium is calculated as follows:

$$E_o = R_o \phi_e = R_o \sum_{a=0}^{\infty} \left(e^{-M} \right)^a w_a m_a \tag{9}$$

where w_a is the weight-at-age and m_a is the proportion of that age class that is sexually mature. We use a simple logistic function to describe maturity-at-age:

$$m_a = \frac{1}{1 + e^{-g(l_a - l_h)}} \tag{10}$$

where g is a shape parameter that describes the variation in maturity-at-age, l_h is the length at 50% maturity and l_a is the mean length-at-age.

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4.2.2. Population dynamics

We initialize the numbers-at-age (N_a) matrix assuming a stable age distribution and the oldest age class (A) is a plus group containing individuals ages A and older:

$$N_a = \delta R_o (e^{-M})^a \tag{11a}$$

$$N_A = \delta R_o \frac{(e^{-M})^A}{1 - e^{-M}} \tag{11b}$$

The δ parameter is constrained to the interval [0-2] and represents the ratio of initial numbers to the unfished equilibrium numbers. Numbers-at-age are propagated over time using historical catch information and size selectivity to calculate age-specific fishing mortality rates. Since our interest was to develop a fishing mortality rate time series to force Ecosim, annual fishing mortality is conditioned on observed total catch:

$$F_t = \frac{Ct}{Bt} \tag{12}$$

where C_t is the observed total catch from all fisheries combined and biomass is simply the product of numbers-at-age times mean weight-at-age. Given predictions from equation 12, numbers-at-age are updated using:

$$E_t = \sum_{a=0}^{A} N_{t,a} m_a w_a$$

(13a)

$$N_{t+1,1} = \frac{\alpha E_t}{1 + \beta E_t} e^{\omega_t \sigma} \tag{13b}$$

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$$N_{t+1,a+1} = N_{t,a} e^{(-M - F_t v_a)} \qquad \text{for a < A} \tag{13c}$$

$$N_{t+1,A} = N_{t,A-1} e^{(-M - F_t v_a)} + N_{t,A} e^{(-M - F_t v_A)} \qquad \text{for a=A} \tag{13d}$$

Equation 13a represents the total egg production in year *t*, and equation 13b is the Beverton-Holt recruitment function; note that process errors ω_t may be included if $\sigma > 0$. The instantaneous natural mortality rate is represented by *M* and the vulnerability-at-age (v_a) is calculated using the same logistic function in equation 10. However, separate parameters (*g* and l_h) are used and unless otherwise noted are fixed values (i.e., not estimated).

4.2.3. Estimating model parameters

Model parameters were estimated by fitting the models to time series data on relative abundance and composition information if available. All abundance indices were assumed to be proportional to stock size or a specific component of the stock such as age-0 recruitment indices. We also assume that observation errors are log normally distributed. In the case of relative abundance indices the observation model is:

$$Y_t = qX_t e^{v_t} \tag{14}$$

where X_t is the predicted biomass or age group or population numbers (depending on what the observation Y_t represents) and q is simply a scaling parameter or the slope of the regression between *Y* and *X*. The scaling parameter, *q*, is a nuisance parameter and we simply integrate over this parameter as well as the variance in the observation errors using the methods suggested by Walters and Ludvig (1994). In short, this method uses the maximum likelihood estimates for *q* and the variance in the likelihood kernel, thus each

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independent observation series is weighted by the relative standard deviation in the observation errors. The corresponding negative log-likelihood is:

$$\ln l_Y = -\frac{(n-1)}{2}\sum_{i=1}^{n}\left(Z_t - \bar{Z}\right)^2 \qquad (15)$$

where $Z_t = \ln(Y_t/X_t)$ and

$$\bar{Z} = 1/n\sum Z_t = \ln(q) \qquad (16)$$

In cases where catch-at-age information is available, a multinomial likelihood is added to the overall objective function and here we assume no aging errors and that the catch-at-age composition is representative of the age-structure in the Chesapeake Bay region. The negative log-likelihood for the multinomial distribution is:

$$\ln(l_a) = -\sum_{t=1}^{T}\sum_{a=1}^{A} n_{ta}\,\ln\left(p_{ta}\right) \qquad (17)$$

where n_{ta} is the observed numbers-at-age in the catch sampling programs and p_{ta} is the vulnerable proportion-at-age based on the numbers-at-age and vulnerability schedule in the population dynamics model.

For the majority of the assessments we assumed only observation errors and limited the unknown parameter set to (R_o, k, and δ). In cases where catch-at-age data were available, we also estimate parameters for the selectivity function (g and l_h). We did not attempt to estimate process errors or recruitment anomalies, in any of the assessment models.

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4.3. Stock reduction analysis

Kimura's 'stock reduction analysis' (SRA) can be used to analyze long-term data in stock assessment. Here, historical catches are treated as fixed, known quantities ('conditioning on catch') and are subtracted from simulated stock size over time so as to aid in estimating how large (and/or productive) the stock must have been in order to have sustained those catches and to have been reduced by some estimated fraction from its historical level.

4.3.1. Using Ecosim for stock reduction analysis

A drawback of treating catches as fixed values as is commonly done in SRA, is that catches, in fact, arise from the interaction of fishing effort and abundance. Ignoring this dynamic interaction amounts to treating the catches as purely depensatory impacts on stock size. As a consequence, the fixed catches can cause progressively larger calculated fishing mortality rates F, if simulated stock size declines. This may lead to a depensatory spiral of rapid collapse in the simulated stock, which may or may not have been possible in the real system.

We are using a modified version of Kimura's SRA in Ecosim where catch series can be treated as a forcing input (with simulated F calculated each year as (input catch) / (simulated stock size)) or, alternatively, be used for evaluating model fit only where F values are available from assessments. We use this SRA for groups where we do not have reliable trends of stock sizes and where we, thus, are unable to use the stock assessment methodologies discussed earlier.

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5. Ecopath Model of Chesapeake Bay

The work to construct an Ecopath with Ecosim model for Chesapeake Bay has been underway for three years and has involved a large number of scientists from the Chesapeake Bay area supported by modelers from the University of British Columbia where the methodology development is centered. An initial workshop was held in October 2001 to introduce the modeling approach to the Chesapeake Bay research community, and to discuss an early version of the Fisheries Ecosystem Model in order to look for gaps in parameters, missing trophic linkages and potential data sources to address concerns. A major aspect of the workshop was to formulate research questions that can be addressed by ecosystem modeling (Table 1). The present report addresses some of the questions in the table as discussed later.

An introductory seminar/lab course on the use of the Ecopath portion of the EwE software was conducted in February 2002 with a follow-up on dynamic simulation modeling in May 2002 at the Smithsonian Environmental Research Center, Edgewater MD. A second workshop to develop the Chesapeake Bay EwE model was held at the Virginia Institute of Marine Science, Gloucester Point VA in May 2002 to further develop the model and discuss its parameterization.

As a next step a modeling workshop was held at the National Fish and Wildlife Service's Patuxent Wildlife Visitor Center in Edgewater, Maryland, April 28 – 29, 2003. Some noteworthy results from the workshop include,

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- Agreement that the ecosystem model with 45 major species groups as it is currently implemented reproduces many of the important time series trends well;

- Recognition that there remains a need to incorporate (or link to) water quality parameters, abiotic processes and lower trophic level dynamics;

- Recognition that there will be tradeoffs between many of the stated objectives of the Chesapeake 2000 Agreement. With finite ecosystem resources, it is unrealistic to believe that all fish species can be returned to their historic peak levels of abundance.

As part of the 2003workshop, some adjustments were made to the parameterization of species at lower trophic levels to secure both better data quality and better resolution. More reliable data were incorporated for the biomass of zooplankton, and oyster groups. Further, abundance indices and a new life history stage were introduced for oysters. The intention was to capture dynamics and mortality differences influenced by oyster population ontogenetics. It is expected that the Chesapeake Bay model under development will serve as a template for future modeling efforts of other specific groups or for improved modeling of the present groups.

We refer the reader to the Chesapeake Bay ecosystem modeling webpage (http://noaa.chesapeakebay.net/ecosystem.htm) for more information about the development and progress of the project.

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5.1. System boundaries

Several groups being modeled reside in the Chesapeake Bay but are considered as parts of larger 'stocks' usually encompassed by the eastern or northeast U.S. Further complicating matters, many of the groups spend only part of the year or different parts of their life histories within Chesapeake Bay. Thus, in order to derive time series for EwE time simulations, it is often necessary to develop assumptions and correction factors such that stock assessments for a larger population can be applied to the CB EwE model.

5.2. Time periods covered

The strength of any model to be used for testing management action outcomes, is related to how it can be validated based on observed data for that system. This is true whether that model is a traditional single species or a multispecies model. To that end, the modeling process involved construction of two ecosystem model. First a 'present day' model of the Chesapeake Bay was constructed to take advantage of the more abundant, recent information. Then, we modified the parameters of the present-day model to represent roughly what the system may have looked like 50 years prior, creating a '1950 model'. This model was then run dynamically and tuned to various observed data or to data estimated from other models.

This document focuses on the 1950-model, and we do not present any data tables etc. for the present-day model, but we do describe most of its parameters. The changes to the present-day EwE model to construct the 1950-model are presented in the following sections. For many groups no changes were made, either because of a lack of available information on how they may have changed, or because no change was deemed necessary for those groups. Groups for

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which no changes were made are, with a few exceptions, not noted below. Also included are descriptions and sources for the various time series data used in tuning the model. Note that several of the new time series data sets are based on new and preliminary stock assessments undertaken by the authors and others.

6. Data types, sources and estimates

6.1. Basic parameters and catches

The basic parameters for Ecopath models, with their units of measurement and commonly used abbreviations, in parentheses are

- biomass ($t \cdot km^{-2}$, B)
- production per unit biomass, i.e. total mortality ($year^{-1}$, P/B, i.e., Z)
- consumption per unit biomass ($year^{-1}$, Q/B)
- ecotrophic efficiency (EE)
- production divided by consumption (P/Q)
- biomass accumulation ($t \cdot km^{-2} \cdot year^{-1}$, BA)
- fraction unassimilated food (GS)
- detritus import ($t \cdot km^{-2} \cdot year^{-1}$)
- diet composition of species 'i' from prey '$j_1, j_2, j_3, \ldots, j_n$' (fraction, DC)

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- fishery landings and discards by gear sector ‘j’ imparted upon each species ‘j_1, j_2, j_3,…, j_n’ (t · km^{-2} · year^{-1}).

The diet compositions (DC) for all species must be entered. Gear sectors are designated by the user, and the catches and discards by them upon species or species groups in the model must also be entered.

Of the input parameters: B, P/B, Q/B and EE, one may be left as unknown since “the Ecopath model ‘links’ the production of each group with the consumption of all groups” (Christensen *et al.*, 2004) based on the trophic relations mapped out by the DC.

Typically, building an Ecopath model emphasizes collecting data for three of the eight basic input parameters; B, P/B, and Q/B. Other basic input parameters are usually not as well understood for most modeled species. In the case of fraction unassimilated food, 0.2 is set as a default value based on the experiments of Ivlev (1961). While this estimate may be appropriate for carnivorous fish, it may be too low for many herbivorous species, especially high metabolism ones, notably zooplankton where a value of 0.4 results in more appropriate respiration/biomass ratios (Christensen *et al.*, 2004). Because P/B and Q/B are usually entered the P/Q rate will be set by the ratio of user inputs for those values. If however, the modeler is incapable of providing an estimate of either P/B or Q/B then the P/Q ratio may be entered instead. Note that because of the meaning of P/Q high-trophic level predators with low production should have low P/Q values, (e.g., ≈ 0.05, whereas low-trophic level highly productive organisms will tend to have high P/Q ratios, (e.g., ≈ 0.3) (Christensen *et al.*, 2004).

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Ecopath models are 'snapshots' that are intended to serve as basis for time-dynamic Ecosim simulations. For this reason the BA may be entered to represent the rate at which biomass is increasing or decreasing for the species group modeled – Ecopath models do not assume steady-state. This may especially be required in order to improve Ecosim simulations. Lastly, 'detritus import' is only of concern to the detritus group and can therefore be omitted for 'living' groups.

Given these parameter characterizations, most Ecopath users prefer to leave the default values for 'fraction unassimilated food', and BA, only adjusting these values for species that have documented evidence suggesting different values. Because many species have not been studied in enough detail to yield published estimations of B, P/B, or Q/B, the user may decide to have Ecopath estimate one as an unknown while estimating the others. In such cases, it should be borne in mind that P/B and Q/B values to some degree are conservative for similar species in similar ecosystems. This implies that even if one cannot obtain a reliable P/B or Q/B estimate for the species or species group modeled, then estimates for similar (or the same) species in similar (or the same) ecosystem may have to suffice as proxies and, where possible, be modified up or down to reflect differences in exploitation pressure. Where biomass estimates are unavailable, they can be left for Ecopath to estimate given that the user can provide a value for EE, i.e., the fraction of production used in the ecosystem (Christensen *et al.*, 2004).

One final word about general parameterization – on grouping species in an Ecopath model. Species may be modeled as one of three types: 1) an aggregation of trophically similar organisms, i.e., what is called a 'functional' group; 2) a single species group; or 3) as a life

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history stage that is part of two or more groups representing life history stages of a 'multi-stanza' group. Generally, species to be examined in terms of policy questions are best dealt with as single species or multi-stanza groups. Multi-stanza groups are preferred if there may be ontogenetic issues in the species' ecosystem role that could play a part in policy issues to be examined. Because biomasses are often difficult to estimate for larval and juvenile fish life history stages, only the biomass for one group is necessary. Indeed, Ecopath will estimate the stanza biomass and consumption rates after the following lead parameters are supplied: the von Bertalanffy growth (curvature) parameter K (available for fish species through FishBase), B for one ('leading') stanza, estimates of Z (=P/B) for each stanza, Q/B for one stanza, and an estimate of the ratio of the weight-at-maturity to the asymptotic weight, W_{inf}. For a discussion of the calculations used in the Ecopath model, see Christensen and Walters (2004).

In most models, there will be a higher degree of aggregation in species that are trophically distant from the focal species. The desire to enrich the model with detail must be tempered, however, by a realistic examination of the modeler's ability to flesh out that detail and to obtain data or estimates for the required parameters. To examine specific policy issues for any particular species, there must be detailed information available from surveys or assessments, and similar information should be available for species with which the focal species likely interacts with in the environment. In particular, well-documented diet composition data and time series data of biomass, natural and fishing mortality, fishing effort and average weight are required to explore ecosystem relations when applying the time dynamic Ecosim model.

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Input parameters for the models are described below. The basic input parameters, biomass ($t \cdot km^{-2}$), production / biomass (P/B, $year^{-1}$, corresponding to total mortality, Z), consumption / biomass (Q/B, $year^{-1}$), and catches ($t \cdot km^{-2} \cdot year^{-1}$) are described for each functional group in the model, along with a description of how diet compositions were obtained, and of available time series information. A summary of available catch series data is presented in Table 4.

6.2. Diet compositions

Where sources for diet compositions are omitted in the following data sections they were based upon advice from local experts at the Chesapeake Bay Ecopath workshop (Sellner *et al.*, 2001) and general knowledge of these species' trophic behavior as reported in Hagy (2002) and Baird and Ulanowicz (1989).

6.3. Catches

For many species, catches are extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the Chesapeake region and the years 1950-2002. The Chesapeake region includes Maryland and Virginia catches, including catches made on the Atlantic Ocean side. In many cases, we have not corrected the catches for this discrepancy due to a lack of correction factors; however, we do not believe that this contributes any major bias to the analysis. Many of the species in the model for which it potentially may be of concern, are migratory species that spend a major part of the year in the Chesapeake Bay. Typically, they will be spending only a limited part of the year in the coastal waters of Maryland and Virginia outside the Bay, and we anticipate that the catches there as a rule will be similarly limited.

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While the NOAA marine catch database provides estimates for commercial catches from 1950 up to the present it is much more difficult to obtain similar time series for the recreational catches. The official recreational catch databases only include information from 1982 onwards; hence we resorted to an approximate method for deriving estimates of recreational catches for the period 1950-1981. We generally plotted commercial versus recreational catches for 1982 to the present and checked the data for trend. If a trend was clear (which rarely was the case) we would regress commercial versus recreational catches and estimate the pre-1982 recreational catches from the regression. Where no trend was detected, we would use either the arithmetic mean (when there were few outliers) or the median value of the commercial/recreational catch rate to estimate the recreational catches for the earlier time period. For the time period from 1982 to the present, we always used the commercial/recreational catch ratio as estimated from the catches. The estimates of commercial and recreational catches are Atlantic coast-wide for many species and, for lack of better estimates we considered them representative for the Chesapeake Bay as well.

6.4. Time series information

For many groups in the Chesapeake Bay model there is time series information available from catch monitoring, surveys, and stock assessments that can be incorporated into the EwE simulations. EwE thus builds on the more traditional stock assessment, using much of the information available from these, while integrating to the ecosystem level.

The time-series fitting uses either fishing effort or fishing mortality data as driving factors for the Ecosim model runs. A statistical measure of goodness-of-fit to the time series data outlined above is generated each time Ecosim is run. This goodness-of-fit measure is a

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weighted sum of squared deviations (SS) of log biomasses from log predicted biomasses, scaled in the case of relative abundance data by the maximum likelihood estimate of the relative abundance scaling factor q in the equation $y = q \cdot B$ (y = relative abundance, B = absolute abundance). Each reference data series can be assigned a relative weight representing a prior assessment of relative data reliability.

The model allows four types of analysis with the SS measure:

1. Determine sensitivity of SS to the critical Ecosim vulnerability parameters by changing each one slightly (1%) then rerunning the model to see how much SS is changed, (i.e., how sensitive the time series predictions 'supported' by data are to the vulnerabilities);

2. Search for vulnerability estimates that give better 'fits' of Ecosim to the time series data (lower SS), with vulnerabilities 'blocked' by the user into sets that are expected to be similar. The search is typically conducted on the most sensitive interactions, as identified above;

3. Search for time series values of annual relative primary productivity that may represent historical productivity 'regime shifts' impacting biomasses throughout the ecosystem;

4. Estimate a probability distribution for the null hypothesis that all of the deviations between model and predicted abundances are due to chance alone, i.e. under the hypothesis that there are no real productivity anomalies.

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In addition to the nonlinear optimization routines described above, the fit to data can also be improved in a feedback-process by examining some of the crucial ecological parameters in the EwE model (notably total mortality rates and the settings for top-down/bottom-up control). It is important to note here that such fitting does not include any 'fiddling-factors' internal to the model. Instead, the type of question addressed after each run is "Which species parameters or ecological settings are not set such that the model adequately captures the observed trends over time?"

The inclusion of time series data in EwE facilitates its use for exploring policy options for ecosystem-based management of fisheries. In the analyses in this report, we illustrate how the model can be used to address some of the policy questions defined by workshop participants (Table 1). We do not, however, develop this in much detail here. Further development and policy exploration activities will be carried out by the NOAA Chesapeake Bay Office staff in cooperation with local experts and fisheries managers.

Time series information for use with EwE can be of the following types:

- For functional groups,
    - Biomasses information (does not need to cover all years in the time series),
        - Relative biomass series: can be from surveys, assessment, etc.;
        - Absolute biomass: rarely used as it assumes that the absolute values (per unit area) are estimated in the same manner for the original data and for the ecosystem model. Absolute data are as a rule entered as relative data instead, using only the trend in the data for the fitting;

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        - Biomass for forcing: used to force the simulation at each time step; typically used for groups whose dynamics are dependent on processes that are not covered by the ecosystem model;

    - Fishing mortality: used to ‘drive’ the Ecosim model and needs to be entered for all years of the time series;

    - Total mortality: used to compare how the simulation matches the observed data. Data set need not cover all years;

    - Catches

        - Used for comparison of model simulation and observed data or for estimating fishing mortalities based on stock reduction analysis. Data need not cover all years. Time series catch information is presented in Table 4;

        - Can also be used as part of a stock reduction analysis where calculation in Ecosim are made for each time step of growth, mortality, and recruitment, and the catches subsequently are used to estimate a fishing mortality (catch/biomass) which is applied as well;

    - Average weight: used to compare observed and estimated weights for multi-stanza groups;

- For fleets

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    - Effort data by gear type: expressed as relative to the effort in the first year of the time series. Used to 'drive' the Ecosim model. Effort data need to be complete for the time series;

- Environmental data

    - Time forcing data: typically relative primary production (monthly or annual) over the time period, but can be any kind of environmental data as long as it can be related to the productivity for a group.

The actual procedure we applied for fitting the model to time series can be summarized as follows:

- We used the nutrient loading forcing time series from the spatial, hydrodynamic model described elsewhere in this document to force the system productivity in the fitted run;

- We used the 'fit to time series' interface to search for the most sensitive interactions in the model, i.e. those interactions for which the vulnerability setting has most impact on the summed squared residuals between time series and the simulation;

- We did not include catches and estimates from juvenile surveys in the search, i.e., their weighting factor was set to 0;

- We selected the 25 most sensitive consumers and searched for vulnerabilities for these groups. Vulnerabilities exceeding 100 were truncated at this value;

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- We then went through each of these groups, and if comparison of time series and trend from time series (or expected trend where there were no time series, but still expectations) warranted it, we would manually change the vulnerabilities for the group in question to improve time series fit.

- We always changed the vulnerabilities by consumer group, i.e. we only used one parameter per consumer (and for some groups we did not change the vulnerabilities at all).

6.5. Data

In this report, we have separated the fish groups into Commercial and Other fish. The split is not used in the actual EwE model; it is only introduced as a matter of convenience in the report. Likewise, the invertebrates have here been grouped into Commercial and Other invertebrates.

6.5.1. Commercial fish

6.5.1.1. *Striped bass: young of the year (YOY), resident and migratory (Morone saxatilis)*

Striped bass is one of the higher trophic level predators in Chesapeake Bay. It is a prized sports fish and of great value for both commercial and recreational fisheries in the Bay (Hartman, 2003). The present fisheries are the result of a successful recovery effort, which began in the early 1980s with heavily curtailed catch levels after the stock had collapsed. By

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1995 the stock was deemed to have recovered and biomass is now often described as being at or near ‘historic levels’ (Hartman and Margraf, 2003).

Three stanzas (life stages) were created to represent this species: young of the year (YOY), resident, and migratory. These age divisions mirror behavioral changes exhibited by the species on the Atlantic coast (Walter *et al*. 2003) and were based upon discussions with local striped bass experts at workshops sponsored by this project. Young of the year are aged 0-11 months. The resident component is defined as fish less than 711 mm, a length representing the age at which the ASMFC considers striped bass to be migratory. This corresponds to ages 12 – 83 months. The migratory component includes ages 84+ months.

The leading stanza for entry of biomass for this group is the resident component, as biomass estimates for YOY as well as the migratory component of the stock utilizing the Bay are poorly understood. For Q/B the migrant population is the leading stanza. Ecopath thus estimates YOY biomass and consumption rates, resident Q/B, and migrant B, based on the lead parameters, the von Bertalanffy growth parameter (annual K = 0.11, average of FishBase values, Froese and Pauly, 2004) and an estimate of the ratio of the weight-at-maturity to the W_{inf}. For a discussion of the life stage calculations used in the Ecopath model, see Christensen and Walters (2004).

Biomass

A resident biomass for the present-day model was derived from estimates of fishing mortality rates from tagging studies (0.28 $year^{-1}$, Latour, unpublished data) and the catch in the Bay, see below. The resulting estimate is 1.03 $t \cdot km^{-2}$. Based on this we estimate the corresponding migratory stock to be 1.77 $t \cdot km^{-2}$. The total stock of age 1+ striped bass that we attribute to the Chesapeake Bay is thus estimated to be 2.8 $t \cdot km^{-2}$, which corresponds to 31,920 t or 26% of the coast-wide striped bass population.

For the 1950-model, we used an estimate of 1.3 $t \cdot km^{-2}$ as leading biomass for the resident part of the population. To balance the catches of migratory striped bass in 1950 we had to include a negative biomass accumulation of 0.04 $t \cdot km^{-2} \cdot year^{-1}$ for 1950.

P/B

Estimates of Z (=P/B) for resident and migratory fish were obtained from VPA (ASMFC, 2003a) and tagging results (Latour, unpublished results). The ASMFC assumes natural mortality M to be 0.15 $year^{-1}$ (Smith *et al.*, 2000). The average F for the reference years (ages 4-13) used by the ASMFC was 0.32 $year^{-1}$, thus Z = P/B = 0.47 $year^{-1}$. This estimate was used for both of the older stanza in the present-day model. Estimate of Z for YOY is set such that it balances predation pressure.

For the 1950-model we used a higher P/B-estimate, 0.60 $year^{-1}$ for the resident population, and a lower P/B-estimate, 0.35 $year^{-1}$ for the migrant part. For YOY, we used 1.8 $year^{-1}$.

Q/B

For striped bass and most of the fish groups, consumption (Q/B) values were determined by the empirical equation available in FishBase (Froese and Pauly, 2004), which requires that estimates be provided for W_{inf}, average environmental temperature, fin aspect ratio (ratio of the ratio of the square of the height of the caudal fin and its surface area), and food type (detritivore, herbivore, omnivore, or carnivore, Palomares and Pauly, 1998). For striped bass

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Q/B was estimated to 2.3 $year^{-1}$, given the parameter estimates of T = 17 ºC, W_{inf} = 115,760 g, aspect ratio = 2.31, and carnivore diet.

Diet compositions

For all striped bass stanzas, a diet item contributing less than one percent to total diet in a referenced study was not considered for determination of the modeled diet composition. Striped bass YOY diets were derived from three sources: Hartman and Brandt (1995), Rudershausen (1994), and Markle and Grant (1970). Grass shrimp, mysids, stone crabs, and benthic invertebrates were combined as 'other in/epi fauna'. Killifish, naked gobies, silversides, and other small fishes were combined as littoral zone forage fish. For striped bass residents, diet data were found in Hartman and Brandt (1995) and Walter (1999). Grass shrimp, mysids, stone crabs, polychaetes and other benthic invertebrates were combined as 'other in/epi fauna'. For predation upon other modeled multi- stanza groups the following predation patterns were assumed: for predation on white perch, 50% adults and 50% juveniles; on menhaden, 60% adults and 40% juveniles; on blue crab, 100% juveniles (Walter, 1999). Weighted averages were used to determine resident diet using three age-classes. Diet data were weighted 1.0 for ages 1 and 2; 4.0 for ages 3+. For the migratory stanza diets composition data were based on Hartman and Brandt (1995) and Walter (1999). Grass shrimp, mysids, stone crabs, mantis shrimp and other benthic invertebrates were combined as 'other in/epi fauna'. Predation on white perch stanzas was divided as 60% adults and 40% juveniles (Walter, 1999).

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Catches

The distribution between commercial and recreational catches was obtained from Table 1 of ASMFC (2003a) assuming that the Atlantic coast distribution is representative for Chesapeake Bay. The ratio of recreational to commercial catches between the categories is quite variable (average of 1.97 with a standard deviation of 1.48) over the 21 years represented (1982-2002). We therefore used the median ratio of 1.53 to estimate recreational catches from commercial catches for the years prior to 1982.

We estimated the catch distribution between resident (12-83 months) and migrant (84+ months) striped bass from the coast-wide catches reported by ASMFC (2003a), estimating total weight in catch from the numbers in the catch, 1982-2002, and average weight. This resulted in an average distribution by weight in the catch of 52% and 48% for resident and migrant striped bass respectively (standard deviation 10%). We used this ratio to estimate recreational catches for the Chesapeake region from the commercial catches extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov), adding 33% to the commercial catches to account for discard losses (NFSC, 2003). The recreational discard losses were given as 53% in the same report, which we chose not to include in the model due to uncertainty about historical trends for the estimate.

There were no catches listed in the NOAA commercial catch database for 1989; we therefore used the average of the 1988 and 1990 catches for 1989.

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Time series

There were a number of time series available for this important group. Resident and migratory biomass were both represented by data from the ASMFC stock assessment for the year 2000 (ASMFC, 2000b). The fishing mortality series for both stocks were estimated from the same source. The data from the ASMFC are estimated from a virtual population analysis model (VPA), i.e. it recreates the population history by receding back in time and adding catches back into the population, based on an assumed natural mortality. Juvenile biomass estimates were obtained from the Virginia trawl survey.

Table 6 presents biomass estimates of striped bass, and Table 7 fishing mortality estimates for striped bass in Chesapeake Bay. The fishing mortalities for the period before 1982 are assumed values.

6.5.1.2. *Bluefish: YOY and adult (Pomatomus saltatrix)*

Biomass

Bluefish was represented in the model by two stanzas; YOY aged 0 – 12 months, and adults aged 12+ months. The adult stanza was the lead stanza for this group. Adult biomass was based on the F derived from a coast-wide biomass dynamic model (Lee, 2003b) and catches in Chesapeake Bay (Piavis, pers. comm.). M was assumed to be 0.26 $year^{-1}$. The YOY biomass was derived by Ecopath based on estimates of K = 0.26 $year^{-1}$ from FishBase (Froese and Pauly, 2004) and W_m/W_{inf} = 0.20, see Table 9.

The biomass estimate was based upon a delay difference model of the group, tuned to the coast-wide VPA data available from the ASMFC. No changes were made to the Z of YOY.

P/B

A biomass dynamic model (Lee, 2003b) was used to derive coast-wide estimates of F (0.257-0.718 $year^{-1}$) for adult age-classes. Note that coast-wide F's are likely to be higher than Bay-specific F's (Gartland, 2002). With an estimate of 0.25 $year^{-1}$ for M, and a total stock-F estimate of 0.295 $year^{-1}$ (Lazar, 2000), the present-day Z (=P/B) can be estimated to be 0.545 $year^{-1}$. For YOY, Z was estimated in order to balance predation pressure on the stock.

For 1950, we estimated the F for the older stanza to be 0.483 $year^{-1}$, and we used an overall Z of 0.589 $year^{-1}$ for this group.

Q/B

The adult leading parameter Q/B was estimated using the empirical relationship in FishBase as 3.3 $year^{-1}$ assuming T = = 17 °C, W_{inf} = 16,962 g, a fin aspect ratio of 2.55, and carnivore diet.

Diet compositions

Adult bluefish diet was based on information contained in Hartman and Brandt (1995). Anything < 1.0% in the diet was ignored for the model. Butterfish and harvestfish were combined as non-reef demersal fish. The diet data were averaged over 6 months (summer, fall, part-winter) representing the time that they are resident within the Bay. Diet composition for the YOY stanza was derived from Hartman and Brandt (1995) and Gartland (2002), ignoring diet elements < 1.0% of the diet. Bay anchovy and striped anchovy in Garland (2002) were combined as bay anchovy, 'unknown fish' in Gartland (2002) was included with littoral forage fish, and 'shrimp' was placed into 'other in/epi fauna'. Diet data were averaged over the 6 months of residency (summer, fall, part-winter) and over the two studies.

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Catches

Commercial and recreational catches were obtained from the National Marine Fisheries Service (Fisheries Statistics and Economics Division, Silver Spring, MD). Recreational catches cover the period from 1981 to 2002. To estimate the total recreational catches from 1950 to 1980, we used the median fraction (0.195, no time-trend) between the commercial catches and recreational catches for the 1981-2002 period and multiplied the commercial landings by this ratio to backfill the recreational catches prior to 1981. This assumes that trends in historical recreational landings were similar to commercial.

Time series

We were unable to obtain a relative abundance index for bluefish in the Chesapeake Bay region specifically. Consequently, we assumed that coast wide abundance indices for bluefish are representative. Both Ecosim and single-species assessment models were fitted to the same information. Three different time series information were available, see Table 10. Coast-wide trawl survey information (in numbers landed per tow and kg landed per tow) were taken from Lee (2003a) for the period 1972-2002.

Total fishing mortality rates were estimated using a single species assessment model, where the combined recreational and commercial catch data were used to drive the assessment model. Furthermore, an index of 0- to12-month bluefish biomass and adult biomass for the entire period was constructed from the age-structured model (Table 10). Growth, size selectivity and maturity parameters used in the assessment model were taken from Salerno *et al.* (2001) and length-weight relationships from Wigley *et al.* (2003) (provided in Table 9). Prior to 1972, there is no survey information on relative abundance and the uncertainty

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associated with the bluefish abundance during 1950 to 1972 is high. Reported landings prior to 1970 suggest that bluefish abundance was relatively low and as such, the initial biomass ratio to the unfished equilibrium was estimated to be very low (Table 9).

6.5.1.3. *Weakfish: YOY and adult (Cynoscion regalis)*

Biomass

Weakfish was represented by two stanzas, YOY (0-12 months) and adults (12+ months), with adults as the leading stanza. For the present-day model, adult biomass was derived from the coast-wide VPA (Kahn, 2002) adjusted to reflect the Chesapeake Bay proportion (Uphoff, Personal communication)) Specifically, catch data from Chesapeake Bay was compared to that of the entire coast. That fraction was then applied to the overall coast-wide population estimates to derive a population biomass estimate for the Bay. YOY biomass was estimated by Ecopath assuming K = 0.26 $year^{-1}$, from FishBase (Froese and Pauly 2004) and $W_m/W_{inf} = 0.5$.

For the 1950-model, we estimated the biomass using an age-structured model to 0.489 $t \cdot km^{-2} \cdot year^{-1}$.

P/B

F was estimated to be approximately 0.2 $year^{-1}$ in the late 1990s for the coast-wide stock (Spear *et al.*, 2003) and M was estimated to be 0.25 $year^{-1}$ for all stock assessment purposes (Smith *et al.*, 2000). Thus, Z – P/B ≈ 0.45 $year^{-1}$ for the present-day model.

For 1950 we estimated F to 0.585 $year^{-1}$, and we used a Z value of 0.685 $year^{-1}$, i.e., we assumed a lower natural mortality than used in the stock assessments.

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Q/B

The adult Q/B value was the leading parameter, and was estimated as 3.1 $year^{-1}$ using the empirical formula from FishBase (Froese and Pauly, 2004) with T = 17 °C, W_{inf} = 8,850 g, aspect ratio = 1.32, and carnivore diet.

Diet compositions

Both stanzas of weakfish had diet compositions derived from Hartman and Brandt (1995). For both stanzas grass shrimp and mysids were added to 'other in/epi fauna'. Diet data were averaged over 6 months (summer, fall, part-winter) representing residency time in the Bay.

Catches

Information about commercial catches in the Chesapeake region was obtained from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the years 1950-2002. A ratio between recreational and total catches for weakfish on the Atlantic coast was obtained from Tables 1 and 2 of the ASMFC 2003 fishery management plan review for weakfish (Spear *et al.*, 2003), and estimated to average 27% (median 28%) for the period 1982-2002. This ratio was used for all years prior to 1982, while the actual ratio was used for 1982-2002.

Time series

The time series for this model was based on a stock reduction analysis. See Table 11 for growth parameters and Table 12 for tuning time series, estimated biomasses and fishing mortalities.

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6.5.1.4. *Atlantic croaker (Micropogonias undulates)*

Biomass

Little stock assessment data are available for the Atlantic croaker (Desfosse *et al.*, 1999; Austin *et al.*, 2003), although they are one of the most abundant bottom fish in Chesapeake Bay. Good year-classes appear to have sustained relatively high catches for the commercial fishery from 1997 to 2002, and the stock appears resistant to growth overfishing, depending on F assumptions. Abundance estimates were calculated based on sampling area of trawl, 5402 km^2, and on the assumption that the trawl net efficiency is 0.4, based on hydroacoustic data (Hoffman, Personal communication) Abundance estimates were converted to biomass assuming an average weight value from trawl catches. Densities were calculated using an area of 5,402 km^2, and entered into the model under the assumption that those densities apply to entire Bay. These data were based upon unpublished information provided by staff of the VIMS ChesMMAP survey (http://www.fisheries.vims.edu/chesmmap/). The resulting biomass was 1.67 $t \cdot km^{-2}$ and we used this biomass for the 1950-model also, as other time trend information for croaker was lacking.

P/B

An annual total mortality for the Chesapeake Bay stock was estimated to be 55 to 60 % per year (Austin et al. 2003). Using the higher end as a conservative mortality estimate yields a P/B =0.916 $year^{-1}$.

Q/B

Q/B was estimated from empirical relationship in FishBase to be 5.4 $^{year-1}$, assuming that T = 17 °C, W_{inf} = 2580 g, aspect ratio = 1.32, and carnivore diet, (Desfosse *et al.*, 1999)

Diet compositions

About half of the diet for Atlantic croaker was designated as 'imported', representative of their six-month residency period in the Bay. FishBase (Froese and Pauly, 2004) suggests that their diet is made up mostly of demersal invertebrates and some larval fish.

Catches

Commercial catches for the Chesapeake region were extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the years 1950-2002. A ratio between recreational and commercial catches for Atlantic croaker was obtained from Table 1 and 3 of the ASMFC 2003 review of the fishery management plan for Atlantic croaker, and averaged 30% (standard deviation 15%, median 29%) for the period 1981-2002. The average ratio was used for all years prior to 1981, while the actual ratio was used for 1982-2002.

We used the catch series to obtain fishing mortality rates over time using the Ecosim stock reduction analysis.

Time series

Time series abundance data for juvenile Atlantic croaker were available from the VIMS Trawl Surveys (www.fisheries.vims.edu/trawlseine), and are presented in Table 14.

6.5.1.5. *Black drum (Pogonias cromis)*

Biomass

Black drum are managed as a single stock along the continental east coast (Jones and Wells, 2001). No estimate of stock size was available for Chesapeake Bay. Ecopath was made to

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estimate biomass by using an assumed ecotrophic efficiency for 1950 of 0.1. This low EE resulted in an initial biomass sufficient to balance the F's estimated from catches.

P/B

Total annual mortality is estimated to range from 0.08 – 0.11 $year^{-1}$ (Jones and Wells, 2001). In the absence of other evidence, we used the median value of M = 0.095 $year^{-1}$. No reliable estimate of F was available and was assumed, conservatively, to equal M. Thus, Z = P/B ≈ 0.19 $year^{-1}$. The model as outlined does not include any predation on black drum.

Q/B

Q/B was estimated using the empirical relationship in FishBase (Froese and Pauly, 2004) as 2.1 $year^{-1}$, assuming that T = 17 °C, W_{inf} = 57612 g, aspect ratio = 1.32 and carnivore diet.

Diet compositions

The black drum diet composition was based on information made available by the VIMS Chesapeake Bay multispecies monitoring and assessment program (Ches MMAP).

Catches

For the present-day model landings were averaged from 1999-2000, and were about 0.001 $t \cdot km^{-2} \cdot year^{-1}$ (Orner, Personal communication) Recreational catches were obtained from the Maryland Department of Natural Resources data and were about 0.001 $t \cdot km^{-2} \cdot year^{-1}$ over the period from 1986-1996.

To obtain time series for the 1950-model, we extracted commercial catches from the NMFS Statistics for the Chesapeake region and recreational catches since 1981 for Maryland and Virginia state waters. The resulting recreational catches were very incomplete, but if we

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include the years where there were estimates for both states only (1983, 1985, 1989, 1995, 2000, and 2002), the recreational catches of black drum totaled 896 tons while the commercial catches for the same years totaled 132 tons. We used the recreational/commercial ratio of 6.8 as a weighting factor to raise the commercial catches to total catches for the time series.

The catches were used to calculate F-estimates using the stock reduction analysis in Ecosim.

Time series

No time series data were available for black drum (apart from the catches discussed above).

6.5.1.6. *Summer flounder (Paralichthys dentatus)*

Biomass

Summer flounder biomass was estimated from unpublished 2002 data from the VIMS CHESMAP survey. Abundance estimates were calculated based on sampling area of trawl (5402 km^2) and assuming the trawl net efficiency is 0.4. The efficiency estimate is not validated for summer flounder. Abundance estimates were converted to biomass assuming an average weight value from trawl catches. Densities were calculated using 5402 km^2 and assumed applicable to the entire Bay.

For the 1950-model, the biomass was estimated based on an assumed EE of 0.95.

P/B

The summer flounder 2002 advisory report noted that this species is overfished in the Northeast and that was an 80% chance that F in 2001 was between 0.24 and 0.32 $year^{-1}$, having declined from about 1.32 $year^{-1}$ in 1994 (NFSC, 2002a). The more detailed analysis of the stock (NFSC, 2002b) suggests that natural mortality is about 0.2 $year^{-1}$. An estimate of total mortality would therefore be $Z = P/B \approx 0.52$ $year^{-1}$. This estimate was also used for the 1950-model.

Q/B

Summer flounder Q/B was calculated to be 2.9 $year^{-1}$ using the empirical equation available in FishBase (Froese and Pauly, 2004) assuming $T = 17$ °C, $W_{inf} = 12{,}000$ g, an aspect ratio of 1.32, and carnivore diet.

Diet compositions

The diet composition of summer flounder was derived from information provided by the ChesMMAP 2002 bay-wide trawl survey (http://www.fisheries.vims.edu/chesmmap/) using samples from the main stem of the Bay. Anything contribution less than 1.0% of the diet was ignored. Bay anchovy and striped anchovy were combined as one group. The diet category 'non reef associated fish' included spotted hake, silver perch, and northern sea robin. 'Other in/epi fauna' included mantis shrimp and mysids.

Catches

Commercial catches for 'flatfish' in the Chesapeake region were extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the years 1950-2002. The flatfish category was assumed to be dominated by summer flounder, the main commercial flatfish. Recreational data were similar in magnitude across many statistical sub areas (NFSC, 2002b); therefore it was assumed that the recreational catch in Chesapeake Bay corresponded to the commercial catch.

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The catches were used to estimate F-values using the stock reduction analysis in Ecosim.

Time series

The summer flounder stock assessed by NEFSC (2002a) was considered to extend from Cape Hatteras to New England. The summer flounder in the Chesapeake Bay represent a subset of that stock and not a separate population. Therefore the stock assessment for the larger population was used for indicating the changes in the summer flounder group in the model. The biomass series (1982 and after) used in the model were taken from the results of a VPA (Figures A10 and A11), which used ADAPT as the calibration method (NFSC, 2002a).

6.5.1.7. *Atlantic menhaden (Brevoortia tyrannus): juvenile and adult*

Biomass

This species was represented in the model by two stanzas, juveniles (0-23 months) and adults (24+ months), with adults as the leading stanza. For 1950 we used an assumed biomass of 30 $t \cdot km^{-2}$ for the adult group to balance the demand for the stanza, while the juvenile biomass was estimated by Ecopath to 16 $t \cdot km^{-2}$, assuming K = 0.424 $year^{-1}$ based on estimated K from 1992 to 2002 (ASMFC, 2004) and $W_m/W_{inf} = 0.24$. These weights were calculated from length data (ASMFC, 2004), which showed that menhaden mature when their length is 180 – 230 mm, (average 205 mm), and that from 1992-2002, L_∞ averaged 328 mm. By cubing these values the weight ratio for the multi-stanza group was approximated.

P/B

P/B of the two stanzas was derived from M and F values in the Atlantic coast menhaden stock assessment (ASMFC, 2004). M was estimated to be ~1.5 $year^{-1}$ for juveniles, and

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assumed to be 0.3 $year^{-1}$ for age 2+ fish. Since fishery on age 0-1 is negligible the juvenile P/B is approximately 1.5 $year^{-1}$. For the age 2+ group we used a P/B of 0.8 $year^{-1}$.

Q/B

For the adult group we used a Q/B of 7.8 $year^{-1}$, which for the juveniles leads to a Q/B of 15.9 $year^{-1}$ based on stanza-calculations.

Diet compositions

The diet composition of menhaden is poorly understood and only qualitative knowledge of feeding characteristics was available. Much of this knowledge was synthesized by the menhaden working group of the CRC Scientific and Technical Advisory Committee (2002). This report suggests menhaden diet shifts from primarily zooplanktivorous as YOY to almost entirely phytoplanktivorous for age 1+. This qualitative ontogenetic shift was mirrored in the modeled diet, with one third of adult diet designated as 'imported material' to represent the time they spend out of the Bay ecosystem.

Catches

There are two main menhaden fisheries, a reduction fishery (major component) and a minor bait fishery (pound net gear type). The proportion of the Atlantic catches taken in the Bay has increased from 20% before the mid 1960s, to 50% in the 1970s, and to more than 80% since 1980, based on the NMFS catch data. We compare our simulations to two catch series, both based on the NMFS catch database: (1) one where we assume a constant proportion (0.4) of the menhaden catches being taken in the Chesapeake Bay, and (2) one where we use the Chesapeake Bay catches as reported. The reason for this is that the ASMFC (2004)

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assessment is coast-wide, and we do not have Chesapeake Bay-specific information about biomasses.

Time series

We extracted relative biomass and F-series from figures in the ASMFC stock assessment report (ASMFC, 2004). The estimates are representative for the total menhaden population, not just the fraction occurring in Chesapeake Bay, as this fraction is difficult to estimate. Noting that more than 80% of the catches have been taken in the Bay in recent decades we consider this a minor problem. Indeed, since several of the major predators on menhaden also move in and out of the Bay it may well be best to include the total populations.

6.5.1.8. *Alewife / herring (Alosa pseudoharengus / Clupea harengus)*

Biomass

The group also includes blueback herring (*Alosa aestivalis*). Based on an annual average of the four seasonal models in Baird and Ulanowicz (1989) a biomass was estimated, and converted to wet weight. The conversion factor (0.16 g DW / g WW) was determined by taking an average of weight carbon to dry weight and dry to wet weight in Jørgensen *et al.* (2000). The resulting biomass seemed rather low to local experts interviewed for this report. Therefore, the biomass was estimated by Ecopath instead, assuming that the ecotrophic efficiency of these species in the Bay was 0.95.

P/B

Total mortality for this group was based on the P/B for alewife in Randall and Minns (2000).

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Q/B

The consumption ratio (9.4 $year^{-1}$) for this group was the average of Q/B values listed for herring (10.10 $year^{-1}$) and alewife (8.62 $year^{-1}$) in FishBase (Froese and Pauly, 2004).

Diet compositions

Alewife and herring spend a large portion of their life in the open ocean but make annual spawning runs to rivers that feed the Bay and spend about half the year in the Bay. Based on qualitative information available from VIMS (2004) the diet of alewife and herring consists of a mix of mostly zooplankton with some phytoplankton as well.

Catches

Commercial catches of alewife and herring for the Chesapeake region were extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov/st1) for the years 1950-2002. It was assumed that there were no recreational fisheries for these species since neither species is included in the NOAA recreational fisheries database available through the same link as the commercial catches. The catch series was used to estimate F-values based on the stock reduction analysis of Ecosim.

Time series

We obtained a relative measure of alewife/blueback herring abundance from fish lifts at Conowingo Dam (St. Pierre, Pers. comm.), see Table 17. The effectiveness of the fish lifts is reduced in wet years, (e.g., 2000, 2002-2004) compared to years with drier spring months, (e.g., 1997-1999, 2001).

6.5.1.9. *American eel (Anguilla rostrata)*

Biomass and EE

Stock assessments for this group were not available, thus Ecopath was made to estimate biomass by setting EE to 0.5. This relatively low EE estimate was based on well-known aspects of the life history of American eel: they can live for 25 years and leave the Bay to spawn and die in the Sargasso Sea.

P/B

The total mortality, 0.31 $year^{-1}$, was based on P/B for American eel in Randall and Minns (2000).

Q/B

The consumption ratio, 3.1 $year^{-1}$, was obtained from the empirical equation in FishBase (Froese and Pauly, 2004) assuming, T = 17 °C, W_{inf} = 9,065 g, an aspect ratio of 1.32, and carnivore diet.

Diet compositions

The diet composition for American eel was based upon qualitative information found in the American Eel Plan Development report (ASMFC, 2000a).

Catches

Commercial catches of American eel for the Chesapeake region were extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the years 1950-2002. The recreational catch of American eel is very limited (Munger *et al.*, 2002); the species is not included in the NOAA recreational

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catch database, and it is therefore ignored here. It may be noted that from 1987 to 1996 Maryland, Virginia and the Potomac River accounted for approximately 60% of the American eel catch in the US (ASMFC, 2000a).

We used the catches to estimate F-values using the stock reduction analysis of Ecosim.

6.5.1.10. *Catfish*

Catfish are predominantly freshwater species, but also occur in estuarine areas. There are three native species in the Chesapeake Bay, white catfish (*Ameiurus catus*), brown bullhead (*A. nebulous*) and yellow bullhead (*A. natalis*), as well as the introduced channel catfish (*Ictalurus punctatus*) and blue catfish (*I. furcatus*), both of which have economic importance in the Bay, and the rarer flathead catfish (*Pylodictis olivaris*), (www.chesapeakebay.net).

Biomass

Catfish biomass was estimated by Ecopath assuming that ecotrophic efficiency was 0.95, i.e. that the model explains 95% of the mortality of the catfish.

P/B

Total mortality for catfish was based upon the P/B value for channel catfish in Randall and Minns (2000).

Q/B

Consumption/biomass ratio was estimated as 2.5 year^{-1} using empirical relationship in FishBase (Froese and Pauly, 2004) and parameters for channel catfish, T = 17 °C, W_{inf} = 26000 g, an aspect ratio of 1.32, and carnivore diet.

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Diet compositions

The diet composition of the catfish group was based on knowledge of these fishes provided by local experts as part of the Chesapeake Bay area modeling workshops, (Sellner *et al.*, 2001).

Catches

Commercial catch for the combined catfish group was based on catfishes and bullheads in the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the Chesapeake region for the years 1950-2002. Since catfish are limited to freshwater and estuarine areas the Chesapeake region as defined in this database should be representative for the Chesapeake Bay. Information about recreational catches in the Bay was not available, and we assumed that the catches were miniscule and could be ignored. Hence, the commercial catches were assumed to be representative for the group, (Table 4).

Fishing mortalities were estimated from the catches using the stock reduction analysis in Ecosim.

6.5.1.11. *White perch: YOY and adult (Morone americana)*

Biomass

White perch was represented in the model by two stanzas: YOY age 0–12 months, and adults aged 12+ months. The adult stanza was the lead stanza for this group. The biomass for the adult group for 1950 is a guessed value. YOY biomass was estimated by Ecopath assuming:

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K = 0.10 $year^{-1}$, an average of values from FishBase (Froese and Pauly, 2004), and W_m/W_{inf} = 0.1.

P/B

Otolith aging from the Choptank River indicated that M = 0.15 $year^{-1}$ for adults (Casey *et al.*, 1988). A biomass dynamic model of white perch (Uphoff, pers. comm.) suggested that fishing mortality from 1996 to 2000 averaged F = 0.54 $^{year-1}$. However, these data showed that in recent years, F was increasing, therefore F = 0.6 $year^{-1}$ was used to calculate P/B = 0.75 $year^{-1}$ for the present-day model. For 1950, an estimate of 0.5 $year^{-1}$ was used. The YOY P/B was assumed to be 2 $year^{-1}$ for 1950.

Q/B

The consumption ratio of white perch adults, 4.2 $year^{-1}$, was estimated with the equation in FishBase (Froese and Pauly, 2004) assuming T = 17°C, W_{inf} = 2178g, an aspect ratio of 1.32, and carnivore diet.

Diet compositions

The diet composition of YOY white perch in the model was obtained from Rudershausen (1994), which used beach seine and trawl sampling were to collect juveniles in the James River. Anything < 1.0% in the diet was ignored and decapods, mysids, polychaetes, amphipods etc. were combined into 'other in/epi fauna'. Fish as prey items were assumed to be littoral zone forage fish. A small portion of 'imported food' was used to account for insects and insect larvae. The diet of white perch adults reflected that it is widely known to consist almost entirely of benthic invertebrates (Luo *et al.*, 1994). Because this preference appears to become greater as the fish age (St-Hilaire *et al.*, 2002) the adult white perch diet is almost entirely 'other in/epi fauna', with some small fishes also included.

Catches

Data to estimate commercial catch were supplied by D. Orner (pers. comm.). Recreational catch data were provided by J. Uphoff (pers. comm.) We do not have documentation for these estimates.

F-values were obtained using the stock reduction analysis of Ecosim.

Time series

Biomass series for age groups 0 and 1+ were available for 'upper rivers' from the Virginia juvenile trawl survey. These were used here for comparison with the Ecosim simulations.

6.5.1.12. *Spot (Leistomus xanthurus)*

Biomass

The biomass of spot was estimated by Ecopath by setting the ecotrophic efficiency to an assumed value of 0.90. This value was chosen in order to obtain a value for catch from biomass · fishing mortality corresponding to the catch estimate for 1950.

P/B

The annual mortality rate for adult spot has been estimated to be 80%, i.e., $Z = P/B \approx 1.6$ year^{-1}, with a maximum life span of five years, and few fish over three years old are found (Pacheco, 1962; cited by Homer and Mihursky, 1991). We consider this mortality estimate to be on the high side, and instead used a lower guessed value of $Z = 1$ year^{-1}.

Q/B

The consumption ratio of spot was estimated as 5.8 year^{-1} using the empirical equation in FishBase (Froese and Pauly 2004), assuming T = 17 °C, W_{inf} = 466 g, an aspect ratio of 1.39, and carnivore diet.

Diet compositions

The diet composition of spot was adapted from Homer and Mihursky (1991) and adjusted to reflect migration, although juveniles are present nearly all year round.

Catches

A time series of catches in the Chesapeake Bay was estimated from the commercial catches in the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov), and the ratio between recreational and commercial catches reported by Desfosse *et al.*(2001), see Table 20.

Time series

We obtained estimates of relative biomass and fishing mortality for the period 1950-2002 from a stock reduction analysis based on catches and tuned to the mean of the VIMS survey estimates for age group 0 and 1+ (Table 21.)

6.5.1.13. *American shad (Alosa sapidissima)*

Biomass

A present-day American shad biomass was estimated from an annual average of the four seasonal models in Baird and Ulanowicz (1989). The original value was converted from

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gram carbon to wet weight using a conversion factor of 0.16 gC/gWW. This conversion ratio was determined by taking an average of weight carbon to dry weight and dry to wet weight for fish in Jørgensen *et al.* (2000). Estimates for 1950 are unavailable, and we assumed a biomass of 0.4 $t \cdot km^{-2}$. Based on the assumption that biomasses were declining in the 1950s, we assumed a biomass accumulation rate of -0.05 $year^{-1}$ for 1950.

P/B

Total mortality for shad was based upon P/B for alewife (*Alosa pseudoharengus*) in Randall and Minns (2000).

Q/B

The consumption ratio for shad, 3.5 $year^{-1}$, was estimated with FishBase, assuming t = 17°C, W_{inf} = 5.500 g, an aspect ratio of 1.32, and carnivore diet.

Diet compositions

Shad diet composition was derived from Walter and Olney (2003), which used percentage by weight from diet analysis of adult shad during their spawning run in the York River, VA. Diet items contributing < 1.0% of the diet were ignored. YOY shad were assumed to eat 100% mesozooplankton (Hoffman, pers. comm.), and to reside in the Bay from April to November. Therefore, YOY diet composition is one third 'imported' matter. For adults, calanoid copepod food items were included as 'mesozooplankton' and mysids as 'other in/epi fauna'. About one third of the adult diet was assumed to be 'imported' to account for migratory behavior. To generate final input values, we calculated weighted averages for the diet items based on 8 age-groups (juveniles plus 7 'adult' age-classes). We assumed adults ranged from age 3-9.

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Catches

Commercial catches of American shad for the Chesapeake region were extracted from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov) for the years 1950-2002. The recreational catch was assumed to be minimal in comparison and therefore ignored. The catches were used to obtain F-values based on the stock reduction analysis in Ecosim.

Time series

Assessments of American shad in the mid-Atlantic were presented by ASMFC (1998). The assessment gives estimates of population size and fishing mortality for the Upper Chesapeake Bay (Table 22). A time series of American shad (as well as of hickory shad) abundance is also available from the fish lifts in Conowingo Dam, see Table 17. However, these estimated could not be used to directly to drive the Ecosim simulations, due to missing information for the earlier part of the simulation periods as well as uncertainty about the population-level fishing mortality rates.

6.5.2. Other fish

6.5.2.1. *Bay anchovy (Anchoa mitchilli)*

Biomass

A recent biomass estimate for bay anchovy was based on data from Jung (2002), which showed that the standing stock biomass from 1995 to 2000 averaged 34,000 t. With 10,000 km^2 as the area of Chesapeake Bay, the biomass in the late 1990s would have been around $3.4\ t \cdot km^{-2}$. The growth model of Luo and Brandt (1993) suggested a higher biomass of

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around 16 t · km^{-2}. Here, we used the biomass of 3.4 t · km^{-2} for the bay anchovy group for 1950 as well.

P/B

Houde and Zastrow (1991) reported bay anchovy adult mortality rates adults rangung between 89% and 95% annually. Luo and Brandt (1993) suggested that a 95% mortality rate was appropriate for the species, although Jung (2002) found that mortality rates can be higher, and are in fact much higher for larvae and juveniles. Because the 'population' being modeled will be dominated by the biomass of adult anchovy the P/B ratio was calculated based on the 95% mortality rate, i.e., P/B ≈ 3.0 $year^{-1}$.

Q/B

The consumption ratio, 10.9 $year^{-1}$, was estimated with the empirical equation in FishBase (Froese and Pauly, 2004), assuming T = 17°C, W_{inf} = 20g (based on length weight relationships reported by Jung, 2002), an aspect ratio of 1.32, and carnivore diet.

Diet compositions

Bay anchovy diet was based on Houde and Zastrow (1991), which contains a general description of anchovy diet and on Hagy (2002), which reported diet composition as 67% mesozooplankton, 28% microzooplankton, 4% meroplankton (fish larvae, etc.) and 1% suspension feeders. Juveniles were assumed to eat copepodites, and copepod nauplii, which were included as 'mesozooplankton'.

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Time series

We used two time series of relative abundance for comparison with the Ecosim simulations, both from surveys. One is from the Maryland DNR juvenile seine survey going back to 1958 (Table 23), the other is from the VIMS trawl surveys from 1978 onward (Table 24.)

6.5.2.2. *Other flatfish*

Biomass

The biomass of this diverse group, which includes hogchoker, tonguefish, window pane flounder and winter flounder was estimated by Ecopath, by assuming that ecotrophic efficiency was 0.95.

P/B

P/B for this group is based on a value given for flatfish off the Atlantic seaboard in Sissenwine (1987).

Q/B

The estimated consumption ratio of 4.9 $year^{-1}$ was derived using the equation in FishBase (Froese and Pauly 2004), and is the average of Q/Bs calculated for winter flounder, windowpane, and hogchoker as representative species for the group, assuming that t = 17 °C, W_{inf} = 3,600 g (for winter flounder), W_{inf} = 689 g (for window pane), W_{inf} = 188g (for hog choker), an aspect ratio of 1.32, and carnivore diet.

Diet compositions

The diet composition for other flatfish was based on a synthesis of diet information for windowpane, winter flounder and hogchoker in FishBase (Froese and Pauly, 2004) and diet information for hogchoker in Baird and Ulanowicz (1989).

6.5.2.3. *Gizzard shad (Dorosoma cepedianum).*

Biomass

The biomass of gizzard shad was estimated by Ecopath assuming an ecotrophic efficiency of 0.95.

P/B

Gizzard shad P/B was increased to 0.53 $year^{-1}$, an estimate of M from empirical equations in FishBase assuming T = 17 °C, K = 0.18 $year^{-1}$, L_{inf} = 43.6 cm, and no fishing mortality. Previously, a lower P/B for gizzard shad from Randall and Minns (2000) was used, but this was not sufficient to meet predation mortality requirements without a huge biomass being estimated.

Q/B

The consumption ratio, 14.5 $year^{-1}$, was estimated using FishBase (Froese and Pauly 2004) assuming T = 17 °C, W_{inf} = 1,980 g, an aspect ratio of 1.32, and herbivore diet.

EE

The ecotrophic efficiency was assumed to be high (0.95), as it is a common forage fish for which we expect to explain much of the mortality.

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Diet compositions

Publications cited in FishBase (Froese and Pauly, 2004) suggested that the majority of gizzard shad diet is phytoplankton, with some zooplankton included for very large individuals. Local experts at the Chesapeake Bay workshop (Sellner *et al.*, 2001) suggested that phytoplankton should be considered the vast majority of the diet.

Time series

6.5.2.4. *Reef associated fish*

This is a diverse group that includes several species, e.g., spadefish (*Chaetodipterus faber*), tautog (*Tautoga onitis*), toadfish (*Opsanus tau*), blennies (Blenniidae), adult gobies (Gobiidae), and black seabass (*Centropristis striata*). Tautog is considered a priced recreational species along the eastern seaboard; it is slow growing and susceptible to overfishing, and is therefore subject to management as part of SAW/SARC and the ASMFC.

Biomass

The biomass was estimated by Ecopath by assuming an ecotrophic efficiency of 0.9.

P/B

According to a recent coast wide assessment report (Stirratt *et al.*, 2002a) during the period from 1995-2000 F for tautog averaged 0.40 year^{-1}. Assessments assumed a natural mortality rate, M, of 0.15 year^{-1} (Stirratt *et al.*, 2002a; Stirratt *et al.*, 2002b). Therefore P/B for tautog ≈ 0.55 $^{\text{year-1}}$, and this value is assumed to be representative for the rest of the group. We used an estimate of 0.51 year^{-1} for the 1950-model.

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Q/B

The Q/B for this group, 3.1 year^{-1}, was estimated using FishBase (Froese and Pauly 2004), based on data for tautog and assuming that T = 17 °C, W_{inf} = 8688 g, an aspect ratio of 1.32, and a carnivore diet.

Diet compositions

The diet composition of this group was estimated from the diet and food item entries cited in FishBase (Froese and Pauly, 2004) for tautog, toadfish and black seabass. Tautog diet was described as benthic organisms, including mussels, gastropods and crustaceans. Toadfish diet was described as one third fish, 25% gastropods, 25% bivalves, 5% crustaceans and the remainder as plant matter. Black seabass diet was described as mostly benthic crustaceans with some clupeids and zooplankton included.

Catches

Catches for these species are very limited. For example, for Tautog, the total catch reported in the NOAA commercial catch data is 316 t for the years 1950-2002 combined. Consequently, we did not include catches in the model.

6.5.2.5. *Non-reef associated fish*

Biomass

This group was represented by species such as spotted hake (*Urophycis regia*), sea robins (*Prionotus carolinus*, *P. evolans*, and *P. tribulus*), lizard fish (*Synodus foetens*), butterfish (*Peprilus burti* and *P. triacanthus*), and harvest fish (*Peprilus alepidotus* and *P. paru*). Biomass for this group was estimated by Ecopath assuming an ecotrophic efficiency of 0.9.

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P/B

Total mortality was estimated from mortality values empirically derived in FishBase (Froese and Pauly 2004): for spotted hake, 0.49 $year^{-1}$; for sea robins, 0.53, 0.5, and 0.56 $year^{-1}$; for butterfish, 1.85 and 1.19 $year^{-1}$; for harvest fish, 1.33 and 1.26 $year^{-1}$. Values were derived by assuming T = 17 ºC and that total length $L_\infty \approx L_{max}$, when no estimate of L_∞ was available. These values suggest a group P/B of about 1 $year^{-1}$.

Q/B

The consumption ratio of the group was estimated by Ecopath by assuming that the production/consumption ratio for this group was 0.2. The P/Q ratio for most species will vary from ≈ 0.05 for long-lived, slow-growing creatures to ≈ 0.3 for small, fast-growing organisms (Christensen *et al.*, 2004). Given that many of the species in this group tended to be small and fast-growing, e.g., butterfish and harvest fish, while others were slower to mature, e.g., sea robins the P/Q estimate of 0.2 should be reasonable.

Diet compositions

The diet composition for this group was synthesized from information for each species cited in FishBase (Froese and Pauly, 2004). Spotted hake adults were said to eat a mixture of fish and squid, whereas the juveniles fed upon a mixture of benthos including filter feeders, crustaceans and molluscs. Sea robin adults were described as eating mostly fish, while the juveniles targeted a variety of crustaceans. Lizard fish juveniles and adults were reported as eating mostly fishes. Butterfish and harvest fish were described as feeding on benthic invertebrates and detritus.

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6.5.2.6. *Littoral forage fish*

Biomass

Species that made up this group included striped and rainwater killifish (Fundulus majalis and Lucania parva), mummichogs (Fundulus heteroclitus), silversides (Membras spp. and Menidia spp.), silverperch (Bairdiella chrysoura), tounguefish (Symphurus plagiusa), and gobies (Gobiidae). The biomass for the group was estimated by setting ecotrophic efficiency to 0.95.

P/B

Total mortality was estimated by local experts at a Chesapeake Bay Ecopath workshop (Sellner *et al.*, 2001) and was assumed to be similar to other forage fish groups.

Q/B

The consumption ratio was determined by setting a production/consumption ratio of 0.2.

Diet compositions

The diet composition for this group was derived from data in Cicchetti (1998), which was reported in percent by volume. The study was conducted at Goodwin Island, at the mouth of the York River. In order to apply the data to the model group anything < 1.0% in the diet study was ignored. Grass shrimp, mysids, polychaetes, etc. were added into 'other in/epi fauna'. Diet data were averaged over the habitats (5) and time period (June - October 1995) covered by the study and were also averaged over species: striped and rainwater killifish, mummichogs, silversides, silverperch, tounguefish, and several species of gobies.

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6.5.2.7. *Sandbar shark (Carcharhinus plumbeus)*

Biomass

Using a model based upon fishing effort, Cortes et al. (2002) suggested that an F_{msy} of about 0.05 was appropriate for sandbar shark and was representative of the likely, present-day fishing mortality. If it is assumed that this was the fishing rate in Chesapeake Bay and if it is further assumed that this fishing mortality rate can be used to back calculate survival, then ≈ 95% of sharks survive fishing each year. Given average recent catches in Chesapeake Bay, from the VIMS FEMAP website (http://www.fisheries.vims.edu/femap), the catch from 1995 to 2000 was ≈ 12 t per year. If this corresponds to a fishing mortality of 0.05, the shark biomass computes to ≈ 240 t, or 0.024 $t \cdot km^{-2}$ for the bay model.

P/B

Cortes et al. (2002) estimated a natural mortality rate of 0.18 $year^{-1}$ for sandbar sharks (> age 1). We thus assume a $Z = P/B = 0.23$ $year^{-1}$ for the modeled period, (present-day as well as 1950).

Q/B

The consumption/biomass ratio of 1.4 $year^{-1}$, was estimated with FishBase (Froese and Pauly, 2004) assuming $T = 17°$, $W_\infty = 616{,}292$ g, an aspect ratio of 1.63, and a carnivore diet.

Diet compositions

The diet composition of sandbar shark was based upon Ellis (2003), who sampled sharks in four size classes; ≤ 60 cm precaudal length (PCL), 61-80 cm PCL, 81-100 cm PCL, and > 100 cm PCL. Giving all size classes equal weight from summed diet data resulted in an

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average wet weight diet of: teleosts (47.9), crustaceans (27.075), elasmobranchs (22.1), cephalopods (1), unknown (1.275), and other (0.65). We used these values as guidelines for the diet, (Table 25).

6.5.2.8. *Other elasmobranchs*

Biomass

This group includes skates and rays, e.g., the cownose ray (*Rhinoptera bonasus*) and other sharks, e.g., the spiny dogfish (*Squalus acanthias*) which are common in the Bay. The biomass was assumed to be similar to that of the benthic rays and skates group of the Southeast US continental shelf model as reported by Okey and Pugliese (2001). The biomass estimate for that earlier model was, in turn, derived from the Southeast Area Monitoring and Assessment Program, (http://www.asmfc.org/).

P/B

The P/B estimate for this group was based on values given for similar groups in other EwE models, e.g., skates in Beattie (2001) and benthic rays and skates in Okey and Pugliese (2001).

Q/B

The Q/B value was calculated by Ecopath by estimating the P/Q ratio for the group as 0.16.

Diet compositions

Diet composition for the group was derived from the ChesMMAP 2002 - Bay-wide trawl survey (http://www.fisheries.vims.edu/chesmmap/), using samples from the main stem of Chesapeake Bay. Data for cownose rays, clearnose skate, bluntnose ray, bullnose ray, spiny

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butterfly ray, southern stingray, smooth dogfish, and spiny dogfish were used. Anything < 1.0% of the diet for any of the noted species was ignored for determination of the group diet.

Time series

6.5.3. Birds and other vertebrates

The EwE model includes two groups of seabirds, piscivorous and non-piscivorous. In addition the odd marine mammal occurs in the Chesapeake Bay, as do 'other vertebrates' in the form of turtles. We have, however, excluded these groups from the 2004-version of the Chesapeake Ecosystem Model due to their perceived minimal trophic and economic impacts. Should ecological considerations warrant explicit inclusion of such groups, this can be easily achieved.

6.5.3.1. *Piscivorous seabirds*

The birds included in biomass for this group were based on advice from local experts, and listed by D. Forsell (pers. comm., workshop October 2001) and are presented in Table 26.

Biomass

The biomass estimate was based on advice provided in a Chesapeake Ecopath workshop (Sellner *et al.*, 2001).

P/B

Total mortality was based on survival rate values of 85-90% for cormorants, and 80-93% for alcids in the Northeast Atlantic (ICES, 2000).

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Q/B

The consumption ratio was from data for the seabirds group in Okey and Pauly (1999).

Diet compositions

The diet composition was based upon advice from D. Forsell (Personal communication).

6.5.3.2. ***Non-piscivorous seabirds***

Biomass

The biomass for this group was based on advice from local experts in a Chesapeake Ecopath workshop (Sellner *et al.*, 2001).

P/B

Total mortality was based on an annual mortality rate of 37% for mallard males and 44% females (Anderson, 1975).

Q/B

The consumption ratio was taken from the estimated Q/B of the herbivorous ducks group in Watkinson (2001).

Diet compositions

The diet composition was based upon advice from D. Forsell (Rugolo *et al.*, 1998, pers. comm.).

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6.5.4. Commercial invertebrates

6.5.4.1. *Blue crab: YOY and adult (Callinectes sapidus).*

Biomass

This species was represented by two stanzas, YOY (0-11 months) and adults (12+ months), with adults as the leading stanza. A recent VPA (A. Sharonov pers. comm.) suggests a current biomass of 1.59 t · km^{-2} for adults. Juvenile biomass was estimated by Ecopath, assuming that K = 0.59 $year^{-1}$ (1998) and W_m/W_{inf} = 0.5. For the 1950-model, we used a higher biomass of 4 t · km^{-2} for the adult blue crab. The feeding time adjustment factor was set to 0.5 for both stanza in order to induce density dependent predation mortality for the juveniles.

P/B

Total mortality for 1950 was assumed at 1 and 5 $year^{-1}$ for adult and juvenile, respectively.

Q/B

The consumption ratio was assumed to be 4 $year^{-1}$ for the adult group and was estimated from multi-stanza calculations for the juveniles.

Diet compositions

Blue crab diet compositions were provided by R. Lipcius (pers. comm.)

Catch

Commercial catch data were available from CBSAC assessments (Rugolo *et al.*, 1997). Recreational catch data were based on Rugolo et al. (2003), who cited NMFS Marine

Recreational Statistics Survey results from the years 1983, 1988 and 1990, and suggested that recreational fisheries accounted for 78.6, 49.5 and 25.9% of the commercial landings respectively. It was assumed, therefore, that the recreational fishery was 25% of the commercial fishery throughout the time period.

Time series

Effort and CPUE for 1945-1994 were available from CBSAC assessments (Rugolo *et al.*, 1997). Biomass time series for juvenile and adult crabs came from surveys, (Table 31). A blue crab F time series was derived from the stock assessment made available online by the Chesapeake Bay Stock Assessment Committee (2004), but not used to drive Ecosim. The age 0 (YOY) and age 1+ (adult biomass) time series, and the total Chesapeake Bay catch time series were from the assessment data presented in the Chesapeake Bay Stock Assessment Committee report (2003a). Note that the abundance indices range around an average value of zero and may, therefore, be negative in some years.

6.5.4.2. *Oyster (Crassostrea virginica)*

Oyster were separated into young-of-year (YOY) and age 1+ stanzas.

Biomass

A biomass of 20.4 $t \cdot km^{-2}$ for age 1+ was used as a leading biomass for the 1950-model based on a stock reduction analysis. A negative biomass accumulation term of 0.42 $t \cdot km^{-2} \cdot year^{-1}$ was estimated as the difference between the 1950 and 1951 biomasses.

P/B

A total mortality rate of 1.5 $year^{-1}$ was available from the model of Dew et al. (2004), where the potential population dynamics of an introduced oyster species (*Crassostrea ariakensis*) in Chesapeake Bay was described. Mortality rates of 6 $year^{-1}$ and 0.15 $year^{-1}$ were used for YOY and age 1+, respectively.

Q/B

A Q/B of 2 $year^{-1}$ was assumed as a leading parameter for age 1+.

Catch

Commercial catches were extracted from the NOAA online database (http://www.st.nmfs.gov) including all oyster catches for Maryland and Virginia. Recreational catch estimates were not available, and were omitted from the analysis.

Time series

Estimates of oyster CPUE for the Maryland harvest were made available by the Maryland DNR Shellfish Division (Table 34, pers. comm.) Oyster abundance and fishing mortalities were estimated from a stock reduction analysis tuned to a CPUE series and are shown in the same table.

6.5.4.3. *Soft clam (Mya arenaria)*

Biomass

Present-day soft clam biomass was estimated from data in Homer et al. (Baker and Mann, 1991). We assume that the population is limited to mesohaline waters (1987). The derivation

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was based on the average of densities from survey sites, assumed body mass of 20 g and that soft clam inhabit 10% of Bay waters. The resulting biomass was 1.66 $t \cdot km^{-2} \cdot year^{-1}$. It was assumed that the biomass of soft clams in Chesapeake Bay has decreased considerably over the last fifty years, but time series data are not available. We estimated the 1950-biomass of soft clam from an assumed ecotrophic efficiency of 0.95 and obtained an estimate of approximately 7 $t \cdot km^{-2}$.

P/B

Brousseau (Abraham and Dillon, 1986) estimates a survival rate for individuals >30mm of 90%, i.e., M = 0.105 $year^{-1}$, whereas in exploited areas the exploitation rate alone has been estimated at 50-60% (2003), i.e., F = 0.69 – 0.91 $year^{-1}$. Assuming for 1950 a low exploitation rate we used a Z value of 0.45 $year^{-1}$.

Q/B

The consumption ratio was estimated by assuming a P/Q ratio of 0.20.

Catch

Commercial catch data were extracted from the NOAA Fisheries Commercial catch database (http://www.st.nmfs.gov), soft clam for the Chesapeake region, and used to force the simulations.

Time series

No actual time series data were available. There are indications, perhaps evidence, that flooding caused by hurricanes may severely affect soft and hard clam in Chesapeake Bay (M. Homer, pers. comm.). We therefore constructed a forcing function to impact the P/B of the two groups based on the occurrence and severity of flooding caused by hurricanes in the Maryland/Virginia region. An overview of the hurricanes is presented in Table 35, while the time series with assumed relative P/B values for forcing the simulations is given in Table 36.

6.5.4.4. *Hard clams (Mercenaria mercenaria).*

Biomass

A present-day biomass was extrapolated from Mann et al. (Lorio and Malone, 1995), based on abundance, area surveyed divided by total Bay area, assuming that a 1-2 inch clam weighs 18-20 g (2004) and that 25% of Bay waters were exploited. The current biomass was thus estimated as 2.24 $t \cdot km^{-2} \cdot year^{-1}$. For 1950 we used an assumed biomass of 4.2 $t \cdot km^{-2}$; higher, to reflect that hard clams have decreased in the Bay over the last decades.

P/B

A total production/biomass ratio was estimated from an empirical equation of Thomas Brey, AWI, included in the Ecopath software, see Christensen et al.(2000) for a description of the algorithm), assuming an average mass of 20 g and water T = 17 °C, non-motile behavior, and an average water depth of 6.5 m.

Q/B

The consumption ratio was estimated assuming a P/Q = 0.20, the same as for soft clam.

Commercial catch

Commercial catches were extracted from the NOAA Fisheries Statistics online database (http://www.st.nmfs.gov), based on quahog, or hard clam, *Mercenaria mercenaria*, for the Chesapeake region, and used to force the simulations.

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6.5.5. Other invertebrates

6.5.5.1. *Ctenophores (Mnemiopsis spp.)*

Biomass

Present-day biomass was estimated from data obtained from the VIMS ChesMMAP survey (http://www.fisheries.vims.edu/chesmmap/). This estimate was also used for the 1950-model.

P/B and Q/B

Shushkina *et al.* (1989) observed in their study that ctenophores in their study had growth rates 1.5 to 2 times greater than jellies. Therefore, the P/B and Q/B values for ctenophores were the values for sea nettles multiplied by 1.76.

6.5.5.2. *Sea nettles (Chrysaora quinquecirrha).*

Biomass

Present-day biomass was based upon an average of the four seasonal models in Baird and Ulanowicz (Shushkina *et al.*, 2000) multiplied by a conversion factor of carbon to wet weight of 0.3% for jellies (1997). This biomass was also used for the 1950-model.

P/B

Hansson (1999) estimated a daily growth rate for *Aurelia aurita* of 0.053 at 5 ºC to 0.15 at 16.5 ºC. The average conservative estimate was the basis for P/B in Chesapeake Bay, i.e., $0.053 \cdot 365 = 19.3$ year^{-1}. Because they are only in the Bay for 3-4 months, an apparent P/B ≈ 5 year^{-1} was used in the model to lower the available production.

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Q/B

Matishov and Denisov found a diurnal consumption rate of 7% of biomass for the medusas in the Black sea. This would translate to an annual consumption per unit biomass of 365 · 0.07= 25.55 year^{-1}. Thus, a 3- to 4-month residency period in the Bay implies a Q/B ≈ 8 year^{-1}. As this value implies a rather high P/Q ratio, we instead estimated Q/B based on an assumed P/Q of 0.25.

6.5.5.3. *Microzooplankton*

Biomass

This group chiefly consisted of rotifers, copepod nauplii and ciliates. A present-day estimate of 0.13 t · km^{-2} was available for the Maryland portion of the Chesapeake (C. Buchanan, pers. comm.). For the models we estimated biomass based on an assumed EE of 0.95, which leads to an estimated value for 1950 of 6.1 t · km^{-2}, i.e. much higher than that estimated for Maryland.

P/B

Total mortality was estimated by local experts at one of the Chesapeake Bay Ecopath workshops (Park and Marshall, 2000). The value was used for the 1950-model.

Q/B

The consumption ratio was estimated by assigning a P/Q ratio of 0.4 to the group.

Time series

For estimates of relative abundance see Table 37.

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6.5.5.4. *Mesozooplankton*

Biomass

This group was largely made up of copepods, which have been noted to reach densities greater than 1000 nauplii per liter at estuarine turbidity maximum zones (Sellner *et al.*, 2001). A present-day biomass for the Chesapeake Bay of 10.323 $t \cdot km^{-2}$ was estimated from Maryland data provided by C. Buchanan (pers. comm.) This estimate was also used for the 1950-model.

P/B

Total mortality was estimated by local experts at the Chesapeake Bay Ecopath workshop (1989).

Q/B

The consumption ratio was estimated by assigning a P/Q ratio of 0.3 to the group.

Time series

Estimates of relative abundance are presented in Table 37 (in the same table as microzooplankton).

6.5.5.5. *Other suspension feeders*

Biomass

Biomass was based on the 'other suspension feeders' group in Baird and Ulanowicz (2000), converted to dry weight, then wet weight using ratios listed for annelids and zooplankton in Jørgensen *et al.* (2000).

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P/B

P/B was taken from a value for annelids in Jørgensen *et al.* (2000).

Q/B

The consumption ratio was estimated by assigning a P/Q ratio of 0.25 to the group.

6.5.5.6. *Other infauna/epifauna*

Biomass

The biomass was estimated by Ecopath, assuming a group ecotrophic efficiency of 0.9.

P/B

The P/B was taken from the value for annelids given in Jorgensen *et al*. (Moore *et al.*, 2000)

Q/B.

Q/B was estimated by assigning a P/Q ratio of 0.2.

6.5.6. Primary producers

6.5.6.1. *Phytoplankton*

Biomass

Biomass for 1950 was assumed at 27 t · km^{-2}.

P/B

P/B was assumed to be 160 year^{-1}.

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Time series

A relative chlorophyll-abundance measure, 1950-1994 was available from Harding and Perry (1997), and was used for comparison with the Ecosim simulations.

6.5.6.2. *Benthic algae*

Biomass

Biomass was estimated based on an assumed EE of 0.9.

P/B

P/B was assumed at 80 year^{-1}.

6.5.6.3. *Submerged aquatic vegetation (SAV)*

Biomass

Four main groups dominate the macrophyte communities within the Chesapeake Bay (Oshima *et al.*, 1999) and one group, eelgrass (*Zostera marina*), dominates these. Biomass ranges from a high in late summer of more than 20,000 t to a low of 5,000 t in December. Total SAV biomass, averaged annually for 1996 was 22,300 t in approximately 25,000 ha, or 2.1% of the total Chesapeake Bay area. Biomass is entered as 419 t · km^{-2}, in a proportion of the total area corresponding to 0.021, for a total of 8.8 t · km^{-2}. This value is also used for the 1950-model due to the lack of time trend information.

P/B

Mortality for *Z. marina* was estimated in a similar system in Japan (Walters *et al.*, 1999) as Z = P/B = 5.11 year^{-1}.

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6.5.7. Nutrient loading

We obtained an estimate of monthly nutrient loading factors for Chesapeake Bay based on a spatial hydrodynamic model as described earlier and in Appendix B, C and D. The model runs are still of a preliminary nature, but are used in lieu of any other time series information describing environmental loading factors through the modeled period.

6.5.8. Model pedigree

Pedigree was defined for all input parameters as described in the EwE User's Guide (Christensen *et al.*, 2004). The pedigree indices were used to obtain confidence interval estimates for the input parameters (Table 40). The pedigree index was estimated as 0.45.

6.5.9. Prices

We obtained prices for the major species exploited in the Chesapeake Bay from the Sea Around Us global price database (www.seaaroundus.org). The price database includes year specific as well as consumer price index corrected values for the various commodities, and we chose to use the prices for 2000 as our intention is to use the prices for evaluating future policy options (Table 41).

For the US recreational fisheries overall, Sumaila (pers. comm., UBC Fisheries Centre) estimated that recreational catches were worth approximately 32 times as much per unit weight of the catch. For our study we used a much more conservative factor of two for the value of recreational/commercial fisheries.

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7. Results and discussion

7.1. Ecopath models

The Ecopath model represents a possible configuration of the Chesapeake Bay model in 1950; its groups are shown arranged by trophic level on Figure 3. The model configuration should be considered a 'possible configuration' meaning that it is mass-balanced to the degree of ensuring internal consistency, there is enough food for the consumers in the model, and enough production to meet any demand. It is not the only possible configuration, however, and we may use the Monte Carlo routines of EwE to explore other possibilities. One way is to use the Ecoranger routine of EwE, where balanced models can be obtained through a resampling method with values drawn, e.g., from the confidence intervals dictated by the pedigree values, (see section 4.1.3 on page 19).

We used Ecoranger to obtain 200 balanced model parameterizations based on the confidence intervals obtained from the model pedigree, and compared the resulting values to the original Ecopath parameters. This is illustrated in Figure 4, where the results are shown for biomasses. There is a clear tendency to estimate higher available production for lower trophic levels and lower production for higher, illustrating that emphasis for model construction should be on constraining the model from the bottom (available primary production) as well as from the top (biomasses and catches of higher trophic level groups).

The Ecoranger runs indicate a lower biomass for black drum as one of the few remarkable results. The tendency for lower black drum biomasses is likely caused by difficulties in

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balancing the hard clam group, which in the original model has an ecotrophic efficiency very close to 1.

We can explore trophic impact in the model through the mixed trophic analysis, developed by Leontif (1951) to describe the American economy, and modified for ecological use by Hannon and Joiris (1989) and Ulanowicz and Puccia (1990). Mixed trophic impacts are shown in Figure 5 for selected groups, and the analysis serves to illustrate, for instance, that alewife and herring show strong impact on many other groups, yet very little is known quantitatively about their history in the Chesapeake.

7.2. Ecosim simulations

Ecosim simulations were performed for the period 1950-2002 using default Ecosim settings except as noted below. Feeding time adjustment was only included for the two older striped bass stanzas, based on experience from other models. For these two groups we also set the 'fraction of other mortality sensitive to changes in feeding time' to zero to reflect that the older striped bass are unlikely to be much impacted by predation. Time series information was as described in the sections above and covers most of the important groups or species in the system.

7.2.1. Vulnerabilities

We estimated vulnerabilities using the procedure described in the methods section and aimed at changing as few parameters as possible. For the fitted run described here, we ended up with the vulnerability settings described in Table 42. In total, we changed the vulnerabilities for 24 groups, using only one vulnerability-setting for each consumer, (i.e., where a group had several prey types, and hence several vulnerability settings, we used the same value for all consumer-prey interactions). We could have used the time series fitting routine of EwE to estimate vulnerability settings for all 218 diet components in the 1950-model. By doing so, we would have increased the model's ability to fit the time series, but it would have been at the cost of its predictive capabilities (Walters and Martell, 2004).

The key criterion for changing vulnerabilities is that there has to be time series information for the group in question, for prey where members of the group are important predators, or for predators, where members of the group are important prey. For many groups, these criteria are not met, and this limits our possibilities for using the model for predictive purposes. If we have no information about what has happened in the past, our capability to explain what will happen in the future is severely limited. We emphasize, that this is a property of all modeling, not a specific feature of EwE.

The vulnerabilities can be interpreted as a measure of how far a consumer is from its carrying capacity in the 1950-start situation. Thus, the default setting of 2 indicates that the given group at most would be able to double the predation mortality it is causing on its prey were it's abundance to increase to its carrying capacity.

7.2.2. Time series fitting

We fitted the 1950-model to whatever relative abundance data were available for the various groups, while catches were used either for comparison with the Ecosim simulation results or to drive Ecosim conditioning on catch. We generally found that where long time series of data on harvests, fishing mortality or relative abundance exists, the model fits well. In the absence of long-term data to drive the simulations, the ability of the model to explain short-

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term ecosystem changes is unclear emphasizing that long-term time series information is of utmost importance for ecosystem-based management of fisheries.

7.2.2.1. *Commercial fish*

Striped bass

For striped bass the assessments only cover the period from 1982 onward. The fit to the biomass trend for 1982-2002 is good for all stanzas along with the fit to catches for the same period. To obtain this fit, it was necessary for both to assume a fairly high fishing mortality for the period prior to 1982, which leads to over-estimation of catches for 1960-1980 for both groups. We could have obtained a better fit to catches for these decades by increasing the 1950-biomass of striped bass considerably. In doing so, however, we would have been unable to make the striped bass return to their 'historic level', and this is an often-stated characterization of the current state of the stock. This is, however, a characterization for which we have been unable to find any concrete supporting evidence. The current simulation thus seems to indicate that if the biomass is back to 'historic levels', then we have overestimated the catches prior to 1982 – where we assumed that recreational catches were 1.53 times the commercial catches.

The striped bass simulation is in agreement with current assessment that the increased fishing mortality in recent years is likely to have caused the stock trend to level off.

Menhaden was assumed to contribute 52.5% and 68.5% to the diet of striped bass, resident and migrant, respectively, in 1950s. Due to decline in menhaden abundance over time, menhaden in the diet was reduced to around 25% for both stanza of striped bass.

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The main conclusion for striped bass is that the assessments should be carried back further than 1982, even if it means obtaining estimates for recreational catch prior to the establishment of the NOAA recreational catch survey system.

Bluefish

For bluefish, the assessment conducted here indicates an increase in the 1950s and 1960s associated with a reduction in fishing mortality, a peak in the mid-1970s, a gradual decline since then to reach the 1950-level again in the mid-1990s, and a small increase again in recent years. This trend is repeated closely by the Ecosim simulation, though the simulations tend to produce higher biomasses and catches during the initial increase and lower biomasses and catches since the peak. The ease with which the general trend was reproduced can be attributed to the assessment and Ecosim being driven by the same factor, fishing mortality, while any trend in their main food is countered by the inverse trend demonstrated by the main competitor of juvenile blue fish, i.e., juvenile striped bass.

Weakfish

For adult weakfish the assessment we conducted indicated a peak in abundance around 1970. This peak is not reproduced in Ecosim, while the trend for the rest of the time period is fitted quite closely. The driving force for the simulation is the fishing mortality estimated in the assessment.

Atlantic croaker

The only available time series for Atlantic croaker is a juvenile trawl series estimate from VIMS going back to 1979. The series is highly variable, with indications of a decrease in recent years (associated with increased catches). The decrease is replicated in the simulation,

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but there is little information on which to base the simulations. We've chosen a low vulnerability setting for Atlantic croaker in the simulations based on a search using the time series-fitting module, but the species is really a typical example of one where there is no foundation for choosing simulation parameters.

Black drum

For black drum the catches can be used for estimating fishing mortalities only if the ecotrophic efficiency in 1950 is assumed to have been very low. This assumption increases the 1950-biomass, which was required to allow the estimated catches to be extracted from the population. The resulting decline is a gradual erosion of the black drum biomass over time caused by the declines in two major prey categories, soft and hard clam. We have no time series information to evaluate the legitimacy of the finding.

Summer flounder

The simulation for summer flounder is confounded by what appears to be unrealistic catch information. There appears to have been a burst of catches in the 1950s and again in the late 1990s. The juvenile trawl series indicates a sharp decline in the 1980s (where there were no catches according to the catch information), followed by a marked increase in the 1990s (where the catches increased markedly as well). Assessments indicate that the summer flounder had high fishing mortality in the 1980s and much lower recently; this is in line with the population trend from the juvenile trawl series, not with the catch information at hand. Hence, with very limited information about potential predator impact on the group and with dubious catch information we consider the simulation for this group unrealistic.

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Menhaden

Menhaden is the only group for which a long-term assessment was available from the regular stock assessments conducted in the Chesapeake Bay region (ASMFC, 2003b). The Ecosim simulation replicates the biomass trend well, even if there is some uncertainty about the early 1950s.

While it was a welcome surprise to find an assessment going as far back as to 1955, we would be even merrier if ASMFC would take one more step and continue back to 1950.

Alewife and herring, eel, catfish, white perch, and spot

The simulations for alewife and herring, American eel, catfish and white perch are all characterized by very little available information on which to drive the simulations and evaluate the results. We chose to condition the simulations on catch for these groups, due to lack of any realistic time series trend. As such, the simulations mainly serve to demonstrate the lack of information about what has happened to these groups in historical time.

For spot we were in a similar situation, but could use the trend from the VIMS survey series to fit a stock reduction model to the catch data. The Ecosim simulation fitted the biomass trend quite well, though it may have overestimated the catches for the 1960s and 1970s. Interestingly, the simulation predicts that the recent increase in striped bass abundance should have impacted the spot abundance, which has, in fact, declined sharply since 1998.

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7.2.2.2. *Commercial invertebrates*

Blue crab

For blue crab we used an effort series from CBSAC assessments to drive Ecosim (Rugolo *et al.*, 1997). The result – based on low vulnerability settings for juvenile and adult blue crabs – is adult biomass and catch trends that resemble the time series trends. The biomass trend, however, is associated with a marked increase in total mortality for adult blue crab, up to around 2.6 year^{-1}, which seems excessive, (see Figure 6). We question if the information on which we based the blue crab simulation is internally consistent.

Juvenile blue crab biomass does not show any time trend in the Ecosim simulations; similar results are obtained from the juvenile trawl survey indices since the 1960s/1970s. Total mortality for juvenile blue crab seems to be declining over time, due to lower predation pressure from adult crabs.

Oyster

For oysters, we had access to some recent trend data, and we estimated the population trend back to 1950 from a stock reduction analysis. The model does not have predation on adult oysters, and it is thus not surprising that we were able to replicate the biomass and catch trends throughout the time periods quite closely – even without invoking any oyster mortality due to diseases. It is generally recognized that diseases are a contributing factor to the current poor stock status for oysters in Chesapeake Bay, but we do lack quantitative information that will allow us to incorporate it in the model. We consider evaluation of historical biomass, catch and other mortality trends important for understanding the role of oyster in the Chesapeake Bay, and encourage such studies.

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Soft and hard clam

Our simulations for soft and hard clam show a marked decrease for both in recent years, much in line with what has happened. Time series information about abundance is, however, wanting, as are information about mortality rates caused by diseases (which are considered important). The decline of clams is the model is caused by the combined impact of sedimentation caused by hurricanes and catches. The simulations for clams should be considered very tentative.

7.2.2.3. *Other groups*

For the remaining fish species, for the birds and for most invertebrates, we had no time series information that could be used to constrain and validate the simulations. Hence, our model is not very illustrative for these groups; they serve mostly as 'place-keepers', i.e., they are there and require resources for their sustenance, their dynamic over time is difficult to evaluate, but in no case do they markedly influence the groups for which we have more information.

7.2.3. Uncertainty/sensitivity

We used the Monte Carlo option in Ecosim to search for a better fit to the time series data, drawing parameters from defined ranges based on the model pedigree. For this we included only time series for the key groups, thus excluding juvenile trawl survey estimates and catches in the estimation of the summed squared residuals (SS). We let the search routine conduct 500 Ecosim simulations (each involving up to several thousand iterations to find a balanced model), but were unable to find any constellation with lower sum squared residuals than we obtained through the fitting procedure.

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7.3. Evaluating policy questions

Emphasis in this report has been on model validation, i.e. on examining model fit to qualify performance and to ascertain whether the model could provide plausible hypotheses for the ecosystem changes that occurred from 1950 to the present. We assume that if the model can successfully mimic system function and recreate historical trends, it lends some credence to its prospective as a predictive tool. Hence, we now intend to use the model to explore some policy questions. We emphasize that the examples we present in this report are but examples, and far from cover the range of questions that the model can be used to address.

7.3.1. Predatory and forage fish ecosystem dynamics

Walters *et al.* (2005) in a recent study concluded that analysis of single species versus ecosystem harvest strategies underlined the need to provide explicit protection for species whose value derives in part from support of other species as well as from harvesting. Harvesting all species at their single-species maximum sustainable yield (MSY) may lead to ecosystem erosion. With this in mind, we examined the role forage fishes play in the Chesapeake Bay ecosystem based on model simulations.

7.3.1.1. *Menhaden and striped bass*

There has been a menhaden fishery in the Bay for many decades, at there is still considerable interest in harvesting menhaden and a major predator, striped bass, which relies heavily on menhaden for much of its sustenance. Striped bass are said to be at their 'historic level' (Hartman and Margraf, 2003), and we here evaluate if their population growth may be impacted by the availability of menhaden – as suggested in recent reports (Uphoff, 2003). If

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the menhaden fishery has any adverse impact is unclear, as "[no] studies have shown that the menhaden purse seine fishery has had any significant biological effect on any other species or fishery" (ASMFC, 2004).

Are the striped bass back at their historic level?

If instead of using the guessed F-values for the pre-1982 period, we use F-values for this period obtained from the Ecosim stock reduction analysis, (i.e. condition the simulations on catches), then it becomes impossible to balance the model for the pre-1982 period, and still reproduce the decline in the 1980s and subsequent rebuilding. We find that we can obtain a similar pattern (while fitting the historical catch series) by increasing the initial biomass of striped bass four-fold. The implication of this, however, is mainly that the biomasses will increase as much again in recent years, still bringing the current biomass back to the 'historic level'.

We do not have much confidence in these results, however. We particularly question what may have happened in the pre-1982 period, where we had to estimate recreational catches based on post-1982 behavior. Again, this calls for a closer evaluation of historical exploitation and trends of the main species in Chesapeake Bay.

Impact of menhaden fishery on striped bass

Using the model as fitted to the time series, we let the model run for an additional 25 years, and evaluate three alternative menhaden-harvest scenarios, *status-quo*, half the fishing on menhaden, and no fishing on menhaden. We find at the end of the simulation that the striped bass biomasses will decrease to half of the current level under *status quo*, that they would double under the reduced fishing scenario, and that they would increase four-times with no

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fishing for menhaden. The striped bass are thus quite sensitive to changes in menhaden fishing pressure in this model.

One of the assumptions in the model is that adult menhaden contributed 44% and 68.5% to the diet of resident and migratory striped bass, respectively. This assumption is based on the study by Griffin and Margraf (2003), based on 916 striped bass stomachs sampled during 1955-1959, (i.e. after an expected decline in menhaden abundance).

We can evaluate the impact of the diet composition by lowering the menhaden component of the diet to 20% for the two older striped bass stanzas, while increasing the diet component of bay anchovy to make up the difference. Doing so has negligible impact on the time series fit for striped bass; it behaves very much like it did in the fitted run, largely because the main prey groups of striped bass change little over time. Evaluating the same three scenarios for menhaden fishing (*status quo*, half fishing pressure, and stop to fishing) we find that the menhaden fishery (as expected) will have much less influence on striped bass. Under *status quo* and half fishing pressure striped bass will remain at the 2005 level, while it will increase approximately 50% under no fishing. A problem with the fitting is that striped bass will rebound to a level approximately twice the 1950-level after the fishing pressure was reduced in the 1980s. This is in contrast to the assumption that striped bass are back at their 'historical level'.

These simulations indicate that assumptions about menhaden contribution to striped bass' diet are indeed important for understanding the dynamics of the menhaden fishery and its potential impact on its predators. We consider the diet assumptions in the fitted model to be

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the most realistic, but note the uncertainty associated with the 1950s population changes for menhaden.

7.3.1.2. *Bay anchovy*

Bay anchovy is considered an important forage species in the Chesapeake Bay at present, and we do indeed have a large number of predators feeding on the group in the present ecosystem model. We used the fitted model to evaluate the impact of bay anchovy on other ecosystem groupings. We increased the simulation period to 100 years, and ran two simulations; one *status quo* maintaining the 2002-fishing pressure for an additional 50 years and recording all group biomasses at the end of the simulation; and another simulation where we introduced a very high fishing pressure on bay anchovy, and again record all biomass at the end of the simulation.

Comparing the ratios of the end-states in Table 43, we note that a few groups are predicted to benefit from the decline in bay anchovy. These are mainly competitors of the bay anchovy, not its prey. A noteworthy result is that striped bass are predicted to benefit, which, we assume is linked to improved feeding conditions for menhaden. The groups that are declining with the bay anchovy are mainly the predators for which bay anchovy are an important prey. We note that the predictions in Table 43 are in general agreement with the mixed trophic impact analysis of EwE, confirming the finding of Libralato *et al.*(MS), who found a strong correlation between Ecosim simulation results and those of mixed trophic impact analysis. However, there are differences. For instance, mixed trophic impact analysis does not predict the impact on striped bass.

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Perhaps the most important finding from this simulation is that one cannot simply assume a direct relation between what happens to a group and what happens to its prey or predators; the food web is more intricate than that.

7.3.2. Invertebrates

The model may lack sufficient detail and be limited by its design in regards to certain lower level processes. Policy questions that concern alterations in planktonic community structure and resulting ramifications on trophically dependent higher trophic-level species, or vice versa, cannot be addressed confidently due to a lack of detail and partitioning at lower levels. This lack of detail at planktonic levels prohibits shifts in community composition due to nutrient enrichment and/or differential responses to predation that may be essential to the reproduction of historical changes in the Chesapeake Bay Ecosystem. The model can easily be modified to provide more detail to accommodate such questions; the main question is whether there is sufficient empirical background to build on.

7.3.2.1. *Blue crab*

When participants in the Chesapeake Bay ecosystem modeling workshop were asked to formulate policy questions (see Table 1), several focused on blue crab. One question dealt with ecosystem manipulation: whether the crab stock can be increased by control of its predators. The model will not be good at answering this question for the simple reason that we could not find evidence of blue crab being important prey for other groups in the system. (Maybe that is why they are so relatively abundant?) The model says that predation pressure on adult blue crab is negligible, and the only important predator on young-of-year blue crab is older blue crab. Hence, we cannot point to any predator control mechanism for enhancing

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blue crab abundance short of providing refuge for small crabs to hide from bigger ones. This may well be a short coming in the diet composition, and we encourage information about predator-prey interactions involving blue crab.

Based on information from CBSAC assessments (Rugolo *et al.*, 1997), indications are that blue crab fishing effort may have increased some four-fold since 1950, while catches have remained fairly stable. We used the model to evaluate if the crab stock can be restored through fishery reductions. We ran the fitted scenario for an additional 47 years, using productivity and exploitation patterns from 2002 for all groups but blue crab, and bringing the fishing pressure back to the 1950-level. The simulation predicts that this would result in a blue crab biomass of 84% of the 1950-level, while catches would settle at 88% of the 1950-level. Thus, indications are that it is possible to restore blue crab abundance and that it can be done through effort restriction with limited impact on overall catches.

If we cut off fishing mortality for blue crab completely, the adult blue crab biomass initially increases drastically for then to level off at approximately twice the current level (once the higher predation on juveniles has reduced the recruitment level). We also observe two- to three-year cycles in blue crab abundance, somewhat like what is observed in the Bay.

7.3.2.2. *Oyster*

The Ecosim simulation shows good agreement with the biomass time series trend available for oysters. Indications are that the oyster biomass over the time period may have decreased to 15% of its 1950-value. This decrease seems rather low compared to the assumptions we have heard commonly expressed, but not quantified, and which we assume to some extent is influenced by the decline in the oyster harvesting industry.

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Noting the Chesapeake 2000 Agreements target of a 10-fold increase in oyster biomass we tried out a ‘what-if’ scenario. Assuming there had been no fishing for oyster since 1950, what might then have happened to the rest of the ecosystem? We shut off oyster mortality due to commercial fishing, and compared the present-day biomass of all groups in the fitted scenario and in the new no-oyster fishing scenario.

The simulation indicates that under a no-fishing scenario oysters would indeed benefit, and today there might have been about 5x the current biomass level. No other group increases by more than 5% in this simulation, while there are 18 groups whose biomass decreases by 5% or more. The strongest declines are among fish species and clams, and are likely related to reduced phytoplankton availability. The simulation raises a question about the effect of decreasing nutrient loading to the Bay as well. This model will likely predict that fish production will decrease even more than the phytoplankton is reduced, based on experience from other models, and, to some degree, supported by empirical studies (Nielsen and Richardson, 1996).

7.3.3. Ecosystem drivers: climate variation and fishing pressure

Based on the hydrographic/climatic model we estimated tentative nutrient loading factors for the Chesapeake. The resulting monthly time series is shown in Figure 8. To evaluate the relative role of the nutrient loading, we note that the summed squared residuals between simulated values and ‘observed’ time series estimates decreased substantially, from 731 to 258, when nutrient loading factors are included.

Estimating “the relative importance of climate variation on fish populations versus that of harvesting pressure” (see Table 1) is a more complicated matter. Or rather, it is something

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that cannot be estimated. We have found systems where it was possible to evaluate population trends based on fishing pressure alone (Christensen, 1998), but it is almost always necessary to consider fisheries as well as environmental factors to explain what has happened in an ecosystem over time (Walters *et al.*, 2005). This is also clearly indicated to be the case for Chesapeake Bay based on the impact of nutrient loading on the residuals as described just above.

8. Conclusions

8.1. Data availability

With this model we are trying to reconstruct the recent history of exploitation and trophic interactions in Chesapeake Bay. The simulations rely very heavily on data availability, seeking, as they do, to reproduce the past. It is a major hindrance to the work that little systematic effort seems to have been allocated in the Bay to collect and make available information from before 1982.

From a data perspective the biggest problem is the lack of pre-1982 recreational catch data. We fully recognize the problems involved in obtaining such estimates, noting that the NOAA Recreational Catch database only starts in 1982, but nevertheless we recommend such data as a priority. It may call for more assumptions than were necessary for the post-1982 data, but it is of utter importance in order to develop an understanding of how life in the Bay has developed and reacted to exploitation.

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The ecosystem model is strongly influenced by nutrient loading trends. Excellent hydrographic/climatic modeling is available for more recent years, but does not cover the full time period required if we are to understand what has happened in the Bay and why. We have applied a simple two-layer, hydrographic model, forced by river gauge data, nutrient loading, wind and rainfall, and based on detailed bathymetry. The model runs are validated based on observed data; it's a simple model, but it provides the time series of estimates required for the Ecosim simulations. We'd very much like to see more detailed models applied to the full time period, in order to link the ecosystem models to those instead and as well.

The striped bass-menhaden simulation discussed above illustrates how assumptions about trophic interactions can be important for evaluating impact of fisheries. We think this warrants a closer look when setting target and limit reference points as part of the stock assessment process. It also calls for digging into the archives to extract historical diet information (as done by Griffin and Margraf, 2003), for continued sampling of diet information, as well as for the creation of databases with available information.

8.2. Stock assessment

Current fisheries management practices are of a tactical nature. They deal with how we best utilize available resources in the short-term. As such, the time horizon considered in the analysis tends to be quite limited as well. In the Chesapeake Bay, hardly any assessment goes back to before 1982. We recognize the role that lack of recreational catch data plays in this, but would like to encourage effort allocated to taking all assessments further back, preferably to 1950.

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When taking an ecosystem perspective, more species than just those that are exploited matter. We recommend assessment of all species of ecological importance in the Bay. When evaluating time series trend for a given species or group, the two most important data points are a biomass from the early part of the modeled time period and one from the late part. Of course, it is valuable to get data points in between or for all years, but it is two at the ends that make the difference. Are there old surveys that may be of use, even for non-target species? Or egg surveys?

Perhaps there should be two standards for stock assessments: one for use in fisheries management, where though decisions with short-term economical consequences have to be made; and another for more academic use, where emphasis is on increasing or understanding of ecological processes and, eventually, for evaluating scenarios of importance for strategic management.

8.3. Spatial modeling

EwE models, as well as their implementation, are very open-ended, i.e. their expansion is straightforward. The number of functional groups is not limited in any way: groups can be removed, aggregated or added as new information is received. Fishing fleets can be added or removed, new fleets can be included (or invented) to test suggested management interventions. Time series data can be easily updated in the time steps required by the user. This requires only that the user create a new spreadsheet with 'comma separated values' (*.csv file) that contains the new data and load it into the EwE database.

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EwE also has the ability to model trophic and fishing effort dynamics in an explicit spatial setting. The spatial component of EwE, Ecospace, is essentially a grid or two-dimensional matrix of 'cells', each cell incorporating an Ecosim model (initially identical as Ecosim inherits its parameters from Ecopath) and expressed at the user-interface level as a map (Walters *et al.*, 1999). Each cell in the map, excluding land cells, is linked through two processes: dispersal of organisms and the redistribution of fishing effort due to changing profit patterns and/or the creation of areas closed to fishing. The user defines the base map (land/water areas) by sketching it on the interface with the computer mouse. Over the top of the base map can be sketched: (1) patterns of relative fishing cost (effort 'avoids' high cost cells, for example, cells far from their home port that require high fuel costs to reach); (2) patterns of relative primary production; (3) patterns of habitats to which biomass pools and fishing fleets can be assigned; and (4) areas closed to fishing (fleet and season specific). This allows for the exploration of policies that include spatial components, including the evaluation of the size and placement of marine protected areas (MPAs). A new sub-module of Ecospace has been developed to evaluate ecological and economic aspects of the placement of MPAs (Beattie *et al.*, 2002).

The geographical scale of a model needs to be defined appropriately to consider the questions that are to be addressed to it. An example of this could be a study of how coastal eutrophication, or nutrient enrichment, influences marine ecosystems. It is known that enrichment (and sedimentation) generally decreases the transparency of coastal water bodies, but the broader indirect effects of such changes in light regimes on continental shelf ecosystems is not well explored. Shelf systems may be particularly susceptible to pollution-related decreases in water transparency as it may cause shifts in energy flows from benthos-

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based to plankton-based food webs. Nutrient loading can be incorporated as a forcing function in Ecosim directly influencing phytoplankton production (as done here) and indirectly, e.g., causing shading effects on benthic producers and the food webs they support. We believe such uses of EwE are of interest as this model is very capable of modeling ecosystem effects through food webs.

Much effort has been devoted to showing the effects of climate changes on fish populations. Most of this work presupposes that there is some connection between climate and recruitment and correlates some climate index with an aspect of the life history of a particular stock of fish, e.g., Hollowed *et al.* (2000) and Francis *et al.* (2002) for production and recruitment of various fish stocks in the North Pacific. The linkages between climate change and fish populations have also been studied in the Atlantic using the North Atlantic Oscillation as a climate index, e.g., Attrill and Power (2002). Ecosim can be used to examine how primary production changes might be driven by climate and evaluate how 'bottom up' cascade of production might differentially affect mortality and stock size of commercially important species in Chesapeake Bay.

Nutrient loading can be incorporated as a forcing function in Ecosim influencing phytoplankton production directly and benthic primary producers indirectly (by simulating interference in Ecosim's 'mediation' tools). Simulated shifts in the system's food webs supported by each of these primary production realms can be scrutinized and compared with related empirical and theoretical information.

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8.4. *Ecosystem boundaries and model structure*

Few ecosystems are clearly demarcated; the Chesapeake Bay is certainly not. Many of the important species spend a good part of their lifecycle or year outside the Bay, and it is an open question how best to model the population dynamics of such species. We believe there is no way but to include the full extent of such populations in the model. For example, for menhaden, this may mean incorporating the entire Atlantic population, its production, consumption and catches. Lesser nuisances, such as ensuring that consumption taken up outside the Bay does not lead to exaggerated estimates for the consumption in the Bay, can be handled by lowering the consumption ratio.

It may well be necessary to make several versions of the fitted model developed here. Different policy questions may call for different model structure. This is not a major problem, only a question of focusing the modeling appropriately. The biggest problem is, rather, that we need information on which to build our models and simulations. We cannot build models designed to answer all questions, at least not without having a very good understanding of how an ecosystem and its components function and what has happened to the resources over time. A model cannot predict what will happen to parts of a system for which we have no information; the model is a formulation of our knowledge.

Based on information and with an appropriate structure, a model can be used to evaluate a range of scenarios and guide us to what are likely consequences and causes. We see a prospect for such use of the ecosystem model presented in this report.

We have sought to clarify what information we have about the ecosystem resources of the Chesapeake Bay and we hope that by assembling the material in one place we have made the

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data gaps more evident. We very much encourage feedback that will enable the next generation of this modeling effort to go beyond what we have presented here.

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11.Appendices

11.1. Appendix A. Phytoplankton biomass and productivity in the Chesapeake Bay

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The data used to estimate phytoplankton biomass includes all the monitoring data that were used to develop Chesapeake Bay estimates of nano- micro- phytoplankton biomass (as

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carbon, chlorophyll, pheophytin, particulate organic carbon, and picophytoplankton biomass (as carbon). The data were processed through the following steps in order to derive whole Bay concentrations. The calculations were revised in January, 2003, to correct for computation errors involving picophytoplankton biomass and segment volumes. Some of the explanations have also been expanded.

11.1.1. Fill in Below-Pycnocline (BP) gaps in the phytoplankton data with estimates based on above-pycnocline (AP) data.

Data for nano- and micro-phytoplankton (cells >2 microns in diameter), chlorophyll, pheophytin, and particulate organic carbon have been collected more consistently and for a longer period of record in above-pycnocline (AP) waters, especially in the Maryland program. Therefore, below-pycnocline (BP) waters are under-represented in the database. For the purpose of estimating BP values and eventually whole water column values for these parameters, adjustment factors were derived that could be applied to AP numbers when BP values were not available. BP:AP ratios of the parameters were calculated for all instances where AP and BP phytoplankton data were collected at biomonitoring stations. The BP:AP ratios varied as a function of salinity and bottom dissolved oxygen so the data were grouped into four environment types:

1. all tidal fresh/oligohaline stations;
2. mesohaline/polyhaline stations that regularly experience summer bottom anoxia;
3. mesohaline/polyhaline stations that border the summer anoxic zone; and
4. mesohaline/polyhaline stations that do not experience summer anoxia.

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Monthly adjustment factors were derived by determining the monthly geometric means for all available BP:AP ratios for each environmental type. (See Appendix A for more detail.) BP values of the parameters were then estimated for all station-date events and inserted into the database where BP values were absent. The BP:AP ratio adjustment factors produced estimated BP concentrations that correlated strongly with measured BP concentrations. A comparison of estimated and measured BP chlorophyll and phytoplankton biomass concentrations in each of the four environmental types shows significant ($p<0.001$) regressions with r^2 values between 0.3 and 0.9 for these two parameters.

Pico-phytoplankton (i.e., cells <2 microns) have only been monitored at Virginia stations, and there is no historical data for Maryland. Samples in Virginia were consistently collected from both AP and BP layers. No estimates of BP biomass were needed.

11.1.2. Weigh the AP and BP concentrations by the AP and BP layer proportions of the mean water column depth of the segment, and sum to obtain whole water column (WC) average concentrations.

AP and BP concentrations of nano- and micro-phytoplankton biomass, pico-phytoplankton, chlorophyll, pheophytin, and particulate organic carbon were weighted according the relative proportion of the water column each layer represented, and then summed to obtain an estimated mean concentration for the whole water column. AP and BP layers are defined in the CBP monitoring programs by the measured depth of the pycnocline or by a prescribed formula (e.g., top half and bottom half of water column). The depth of the AP layer is documented in the event files of the monitoring programs as P_Depth, and AP and BP layers are rarely equal in depth. The relative proportion of the whole water column that a station's

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AP layer represented (AP%) was estimated by dividing the given depth of the AP layer by the *mean* depth of the CBP segment in which the station was located. The relative proportion of the BP layer was 100% minus AP%. Mean depth rather than total station depth was used in the calculation for two reasons. First, bathymetric maps indicate the cross-sectional shape of many Chesapeake segments is tiered, with broad shallow flanks and a narrow, deep mid-channel. Second, many of the biomonitoring stations are located above the mid-channel where total depth is much larger than the mean depth (Table 45). Segment mean depth is therefore more representative of the segment's geometry than station total depth. Station P_Depth was equal to or greater than the segment mean depth in approximately 2% of the data records, indicating a relatively deep pycnocline or no measured pycnocline. In these cases, AP% was set to 100% and BP% to 0%.

11.1.3. Calculate total masses of the phytoplankton parameters, first for each CBP98 segment with a representative biomonitoring station, then for salinity zone.

The estimated whole water column concentrations of each parameter were grouped by station and month of the year, and the geometric mean was calculated for each station-month. The geometric mean was used as the measure of central tendency instead of the arithmetic mean because the phytoplankton data were log-normally distributed. The station-month geometric means were then multiplied by the volume of the station's segment (Table 46) to obtain each parameter's mean mass per segment in each month of the year. Mean mass for segments with the same designated salinity zone were then summed to obtain a total mass (kg) for each salinity zone by month.

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11.1.4. Adjust total masses per salinity zone per month to reflect all Bay segments.

Biomonitoring stations are not located in all CBP98 segments. If we assume the biomonitoring stations are representative of the segments in which they are located, then roughly 87% of the total volume of Bay is represented by the Maryland and Virginia biomonitoring stations and about 13% of the total volume is not (Table 47, "All"). The largest volume without representation occurs in the mesohaline (10.9% of total Bay volume). Nano- and micro-phytoplankton biomass, chlorophyll, pheophytin, and particulate organic carbon were collected in both Maryland and Virginia waters. Salinity zone-specific mass estimates of nano- micro-phytoplankton biomass, chlorophyll, pheophytin, and particulate organic carbon were adjusted with the following multipliers in order to account for the unrepresented 13% of the Bay volume: Tidal Fresh (F), 1.165; Oligohaline (O), 1.238; Mesohaline (M), 1.223; Polyhaline (P), 1.037 (Table 3Table 45).

Picophytoplankton has only been monitored in Virginia waters. If we assume that the monthly mean (geometric) whole water column concentrations in Virginia salinity zones are similar to the comparable salinity zones in Maryland, then picophytoplankton biomass can be adjusted to reflect the expected Maryland biomasses in addition to Virginia masses in waters not represented by biomonitoring stations. Salinity zone-specific mass estimates of picophytoplankton were adjusted with the following multipliers in order to account for unmonitored and unrepresented volumes: Tidal Fresh (F), 4.331; Oligohaline (O), 6.755; Mesohaline (M), 16.328; Polyhaline (P), 1.037. The adjusted total masses for each salinity zone are given in Table 3.

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11.1.5. Masses for Bay and tidal tributaries

Adjusted, salinity zone-specific mass estimates of the phytoplankton parameters were summed for all salinity zones to obtain mass estimates for the entire Bay for each month (Table 3, "All"). These were averaged (arithmetic) across all 12 months to obtain annual means of total mass for the Bay:

- Nano-, micro-, and phytoplankton biomass, 26,996,205 kg carbon;
- Pico-phytoplankton biomass, 4,581,869 kg carbon;
- Total phytoplankton biomass (pico-, nano-, micro-), 31,578,074 kg carbon;
- Chlorophyll, 521,315 kg;
- Pheophytin, 135,953 kg; and
- Particulate organic carbon, 64,565,226 kg carbon.

The total area of the Bay and its tidal tributaries is estimated to be 18,580 km^2 (derived with the Chesapeake Bay 3D Interpolator by D. Jasinski, CBP Data Center). Total Bay mass divided by total Bay area produces the following values:

- Nano-, micro-, and phytoplankton biomass, 1,452.97 $kg \cdot km^{-2}$ carbon;
- Picophytoplankton biomass, 246.6 $kg \cdot km^{-2}$ carbon;
- Total phytoplankton biomass (pico-, nano-, micro-), 1,699.57 $kg \cdot km^{-2}$ carbon;
- Chlorophyll, 28.06 $kg \cdot km^{-2}$;

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- Pheophytin, 7.32 kg · km^{-2}; and
- Particulate organic carbon, 3,474.99 kg · km^{-2} carbon.

An independent check of these calculations was done by Dave Jasinski of the CBP Data Center using the Chesapeake Bay 3D Interpolator Model. Chlorophyll data for every sampling cruise from January 1985 to December 2001 were brought into SAS. To facilitate modeling of the chlorophyll depth profiles, a single total depth was determined for each station from the measured total depths, which can vary with cruise. All measured data below this depth were censored. The data for each station and sampling date were then vertically interpolated, and chlorophyll values were generated for each 1 m depth interval. Arithmetic and geometric means for the entire January 1985 - December 2001 period were then calculated for each station-depth interval. (Note that these calculations do not evenly weight the data by season. Since winter is less intensely monitored than other seasons, these calculations are being slightly biased towards spring, summer, and autumn values.) Next, the station-depth interval means were used in the 3-D Interpolator Model to estimate mean chlorophyll values for all model cells. The station-depth interval means were log-transformed before the interpolation process and then anti-logged after interpolation in order to minimize the effects of algal blooms and plumes. The following chlorophyll masses were obtained for the Bay: arithmetic mean method, 36.98 kg · km^{-2}, and the geometric mean method, 27.68 kg · km^{-2}. The geometric mean obtained with the 3D Interpolator Model using data from all available monitoring stations is very close to the geometric mean of 28.06 kg · km^{-2} obtained with the analysis method described in this paper using only data from the

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biomonitoring stations. This suggests that the total phytoplankton biomass estimate of 1,699.57 kg · km^{-2} is relatively accurate.

11.1.6. Phytoplankton biomass in units carbon

The carbon-based biomass estimates for nano- micro- phytoplankton and picophytoplankton were derived from actual measurements of cell dimensions, calculations of cell biovolume, and taxa specific biovolume-to-carbon conversion factors. The species list has been updated and expanded several times since the report in Appendix B was written, and Richard Lacouture (Academy of Natural Sciences) and Harold Marshall (ODU) will be publishing this separately. The current list is available from Jacqueline Johnson (2003a)

11.2. Appendix B. Chesapeake Estuary Model description

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11.2.1. Overview

The objective in developing a modeling system for Chesapeake Estuary was to integrate information on physical, chemical, and ecological processes into a model for predicting temporal and spatial changes in key indicators of interest to environmental managers. These processes involve variables that can change on various time and space scales, from minutes/meters up to years/kilometers. When faced with such disparate scales in a complex system, modeling generally involves defining a space/time 'window' of primary interest;

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then dynamic variation that is very fast compared to this window is modeled in terms of time-varying equilibria and averages, and variation that is very slow is represented through constant 'parameters'. The window of primary interest for the Chesapeake Estuary Model is a seasonal variation on spatial scales of 1 - 2 kilometers. A model time step of one month is used by Chesapeake Estuary Model to capture this seasonal variation. Based on this window, we elected to treat most physical and chemical processes, such as diurnal variation in wind-driven currents and associated chemical concentration fields, which come to equilibrium on time scales of hours, by calculating equilibrium spatial fields of these variables and then averaging the equilibria over monthly time steps. Longer term variation, such as decadal trends in sea level heights, are treated as constant parameters for any one run of the model that focuses on the window of primary ecological concern.

11.2.2. Physical sub-model

The physical sub-model computes the equilibrium wind- and sea-surface pressure (height) anomaly-driven horizontal currents (and upwelling velocities between the two layers) that will develop after a few hours of steady winds over the model grid, if baroclinic current effects are not large. Coriolis force is also ignored in the model. The model is parameterized so that the user can directly enter desired average current velocities expected in open water from wind stress effects in the west to east and north to south directions. Sea surface height anomalies can be set at the boundaries of the grid. For example, setting the surface height to 0.5 m and 0 m, at the north and south ends of the grid will cause the model to simulate a southerly current through the model grid. The ratio of interface to bottom friction makes the model behave as either a single layer system (surface and bottom velocities equal) if it is set

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to a low value or makes the surface layer move much faster than the deep layer if it is set to a large value (3 - 10).

The horizontal and vertical mixing rate parameters define how much water movement and mixing will occur in addition to the directional movement created by wind driven currents. The chemical distribution simulations assume that all input chemicals (from point or freshwater sources) are initially delivered to the surface water layer via freshwater buoyancy effects, and the vertical mixing rate parameters along with particulate organic sinking and upwelling/downwelling rates provide the modeled mechanisms by which chemicals may reach deep water near the input, see Figure 9.

11.2.3. Chemistry sub-model

Equilibrium chemical concentrations for each month are computed by setting up and solving the sparse linear equation system that results when you set the derivative of concentration to zero in the differential equation defining rate of concentration change in each model grid cell as a (linear) function of inputs (velocities · input concentrations), outputs (velocities · concentration in cell), and internal gain/loss rates (e.g. decomposition = constant · concentration). In the phytoplankton case, each cell is assigned a growth rate equal to a maximum rate times phytoplankton concentration times a Michaelis-Menten function of available phosphorous concentration in the cell (which in turn is computed as total phosphorous minus phosphorous already in phytoplankton in the cell).

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11.2.4. Ecology sub-model

The purpose of the ecology sub-model is to simulate monthly changes in seagrass and epiphyte populations over several years/decades to examine cumulative impacts of the physical and chemistry regimes predicted by the model. Also computed in this sub-model are seasonal changes in photoperiod, water temperature, and light penetration to the sea bottom over the grid. Light penetration patterns are computed from epiphyte and phytoplankton concentrations and are also influenced by suspended particulate concentrations. Phytoplankton growth rates, used to calculated steady state monthly chlorophyll a concentrations, are computed based on the maximum doubling rate, reduced by a factor calculated from a Michaelis-Menten relationship (the Michaelis constant is the concentration of phosphorus resulting in a 50% reduction in the maximum growth rate). Epiphytic algae growth is also controlled by Michaelis-Menten kinetics in addition to a loss rate which represents physical erosion as well as constant grazing. Seagrass growth is computed based on a maximum potential rate adjusted by the difference between photosynthetic gains less respiration losses driven by monthly changes in temperature and light. Seagrass biomass accumulation is also adjusted based on current biomass and salinity. Salinity effects on seagrass growth are implemented based on a Type III functional relationship, with growth decreasing with increasing salinity. The salinity level specified in the dialogue box represents the value where seagrass growth is reduced to 50% of its maximum rate. The salinity power parameter defines the steepness of this curve. Seagrass biomass is calculated as a function of the previous' month's biomass plus the total new growth in the current month less losses due to leaf turnover.

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11.3. *Appendix C. Chesapeake bathymetry data*

Joe Buszowski, Mountainsoft, Canmore Ab., Canada, (joe@mountainsoft.net), and Josh Korman, Ecometric, Vancouver BC, Canada, (jkorman@ecometric.com)

Bathymetry data for Chesapeake Bay was obtained from NOAA's web site at http://rosemary.nos.noaa.gov/servlet/BuildPage?template=bathy.txt&parm1=M130&B1=Submit for a link directly to the data page. The DEM data used was the '1 arc second (Single Big File)'. These data were in a 30m DEM format split into 3 files.

The DEM files were imported into ArcView 3.2 and merged into a single 30m grid coverage using the ArcView extension script 'Grid PIG Tools v2.6', 'Merge Grids' function. The 30m data was then resampled into 1000m and 2000m grids using Grid PIG Tools 'Grid Resample' function. These 1000m and 2000m data sets were then exported from ArcView as ASCII Raster files. The ASCII raster files where then converted into the evm format used by CEM. This process converted the bathymetry measurements into a positive depth measurements as well as converting NULL values (-9999) into -1 to represent land.

The CEM model has limitation on how it allows water to flow from cell to cell. For water to flow between neighboring cells they must be attached via a face. If a cell is not directly attached to the main water body or its only attachment is diagonal (corner to corner) then the cell will be isolated and can not be used properly by the model. CEM also assumes it's outlet to the ocean is defined by cells that adjoin the edge of the grid.

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To meet the flow limitations of the model the evm files were loaded into CEM and edited to remove cells that were not directly attached to the main body, and create an outlet for flow to the ocean, see Figure 10. The evm files were also edited to ensure all significant remaining cell clusters where attached to the main body by a face. This was accomplished by adding cells to join an isolated cluster of cells to the main body. The value of the new cell was estimated by averaging the value of the adjoining cells.

The resampling and editing of the bathymetry data changed the elevation profile of the data. Figure 11 shows a histogram of the resulting data comparing the original 30 m bathymetry data and the 1000 m and 2000 m grids used in the model.

11.3.1. Forcing Data

11.3.1.1. *Freshwater gauged inputs*

River flow data for nine gauged rivers was added to the forcing data file 'CBForce.txt'. See Appendix B, section 'River flows' for a description of how these data were selected and processed.

11.3.1.2. *Precipitation*

Precipitation data for ten stations within the modeled area was average into a single value for the 'Rainfall' data in 'CBForce.txt'. See Appendix D, section 'Precipitation' for a description of how these data were selected and processed.

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11.3.1.3. *Evapo-transpiration Rate*

The evapo-transpiration rate data in ‘CBForce.txt’ are the same as used by the Florida Bay model on which the CEM is based.

11.3.1.4. *Wind*

Wind data for one station was added to ‘CBForce.txt’. See Appendix D, section ‘Wind’ for a description of how these data were selected and processed.

11.3.1.5. *Relative nutrient load*

The relative nutrient load for each gauged inflow has been set to a value of one.

11.3.2. Water Quality data

Point source nitrogen water quality data for Chesapeake Bay was added to the ‘Review Water Quality’ form. See Appendix D, section ‘Total Nitrogen’ for a description of these data.

11.3.3. Changes made to CEM model interface

11.3.3.1. *Modeled areas*

Each modeled area has its own directory that contains all the data and parameter files associated with the area. This is to avoid confusion with parameter files which are initially loaded be a default name. To change the currently modeled area, go to the menu option ‘File->Change Modeled Area…’ and select a new directory. CEM will load the default parameter and data files from the selected directory. The parameter and data files can then be changed

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or saved in the usual way. The name of the current model directory can be read from the 'Current Files' tab on the bottom of the main form.

11.3.3.2. *CEM ini file*

When CEM is first loaded it reads the name of the last model directory from the file 'CEM.ini' in the application directory. If this directory is not valid or does not contain the file 'Baylist.txt' CEM will scan the application directory for the directory 'Chesapeake' or 'Florida' and load the first one it finding as the current model directory. If no valid directory is found then the user will be need to select a new directory to load.

When CEM shuts down the name of the current model directory is save to 'CEM.ini'. The next time you start CEM this will be the directory that is loaded by default.

11.3.3.3. *Ecospace nuo file*

An Ecospace nutrient file *.nuo will be dumped at the end of the model run if the user has entered a file name in the textbox labeled 'Nutrient' on the 'Current Files' tab at the bottom of the main form. To enter a file name double click on the yellow 'Nutrient' textbox or use the menu option 'File > Set Nutrient Export File (*.nuo)...'

11.3.4. Base map editor

11.3.4.1. *New menu options*

'Base Map Files' menu option allows the user to save and restore Base Maps from file.

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‘Legend’ menu option allows the user to load the Legend Editor ‘Show Map Legend Editor…’ and load a legend file ‘Load Map Legend from File…’

11.3.4.2. *Editing Base Maps*

The Map Layer ‘freshwater gauged input locations’ map can be edited saving the grid row and column values of the new location to the forcing data file, ‘CBForce.txt’ for Chesapeake Bay. The new location will be for the currently loaded grid resolution only. Other resolution grids will not be affected. The UTM or latitude longitude coordinates of the input will not be affected by the edit. These data will still reflect the original location of the gauge.

11.4. Appendix D. Hydrographic and climatic information for Chesapeake Bay modeling

11.4.1. Precipitation

Monthly total precipitation data was available for Chestertown MD, Conowingo dam MD, Solomons MD, Salisbury MD, Wicomico MD, Annapolis MD (by combining figures from the United States Naval Academy and the Annapolis police barracks), Unionville MD, Norfolk VA, Fredericksburg VA, and Warsaw VA. This data was found at the NOAA National Climate Data Centre, specifically, the section for co-operative precipitation stations; www.ncdc.noaa.gov/oa/climate/online/coop-precip.html

The time span covered for each station varies, and not all cover the period of interest for the reference data needed for the CB spatial model (1950-2002). Thus the stations listed above

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were chosen as representative of the geographic extent of the CB region, while being adequately stocked with data to cover the time period of interest. If data points were missing then values were inserted equal to the average for that month from the previous two and following two years. The data was in expressed in hundredths of inches by year and month, and were converted to inches for the final time series data set.

Two stations did not have complete data sets (Solomons MD and Unionville MD). For Solomons MD data from 83 onwards was generated by correlation to rainfall at Warsaw VA, (which had the highest correlation to historic Solomon's data of all other stations in the analysis r^2= 0.529). For Unionville MD the 1997 data were based on correlation analysis with Connowingo data (r^2= 0.563).

The time period available for this data was up to the end of 1997, thus the last five years of data for all stations had to be generated via an estimation technique. NOAA precipitation data is available at a cost of $US 20 per station, but this was deemed too expensive to justify. Data was freely available for the monthly rainfall at Washington DC, however at the cities section of the NOAA National Climate Data Centre web page;

www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html

A reference index based on multiplier values of rainfall measured in Washington DC for each month (in 1998-2002) was divided by the average for that month over the five year period. The resulting year and monthly (January 1998 – December 2002) values were then multiplied by the average for each station for that month to fill in values from January 1998 to December 2002. This assumes a rough correlation between rainfall in Washington, and the

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other stations of the region. This was supported by a graphic analysis of the time series data for the 1950 to 1997 data for Washington DC, and all other stations.

11.4.2. Wind

Wind data was available on a daily basis from 1985 to 2002 at the NOAA National Bouy Data Centre website, http://www.ndbc.noaa.gov/cwind.shtml

Only two stations were available for the CB region and the one selected was Station TPLM2 - Thomas Point, MD 38.90 N 76.44 W (38°53'54" N 76°26'12" W). The data was reported as wind speed (m/s) averaged over an eight-minute period once for each hour of the day. Missing data was common and dealt with according to three rules, depending on the length of time lost. For up to 12 hours, the average of the two blocks of equal time both before and after the missing values were inserted, the assumption being that at so short a time scale the daily weather behavior around that time block would accurately predict it. Correlation analysis showed that for the 1985 data the prediction method compared to the actual data resulted in an r^2 value of 0.81. For 12 hours to 9 days 23 hours the data were deleted, and average monthly data calculated without that time block. For 10 days or greater the average for that date and time over the five previous and five succeeding years were inserted on the assumption that climatic mean data would account for this longer term missing data. It must be noted that after 1996 the data set was very poor (more than 200 errors per year in data records, though never in long time spreads) so all missing data was simply deleted for this time period.

Sine and cosine functions were used to convert each hourly wind direction and speed to an x and y vector, which were in turn used to find average monthly wind directions. The average

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velocity of the wind; however was generated by simply averaging the wind speed scalar values for each month. The average monthly direction of the wind was calculated by determining the average x and y vector for each month and converting that to a radians scalar. Thus, the final x and y vectors are combinations of the average of the wind speeds for any given month, and the average direction for the x and y components for each month.

In order to generate historical average winds for 1950 to 1985 two trigonometric functions were used to approximate monthly values. For both the x and y vectors the formula was,

$$\text{vector} = \text{alpha} \cdot \text{SIN}(\text{RADIANS}(\text{beta} \cdot \text{month}/12 \cdot 180)) - \text{gamma}$$

in which alpha, beta and gamma are parameters describing the sine wave height, steepness and intercept of the x and x-axes, and month is a number from one to twelve corresponding to the calendar month, i.e., Jan = 1, Feb. = 2, etc. Each vector was calculated independently and the Excel Solver was used to minimize the sum of squared differences between real and estimated data for a reference time series made up of the known data from 1985 to 2002. Another method to estimate wind data was simply taking the average wind vectors for all months. When this data was subjected to a summed square difference comparison to the real data it was seen to be smaller than the trigonometric analysis. Thus the historic estimated winds are simply the average monthly absolute velocity scalar value applied to the average monthly direction values. The only problem with either method was a complete inability to predict extreme events. That is, the predicted values have diminished amplitude compared to real values. This should be borne in mind during model simulations because it suggests that any anomalous wind events, (i.e., those of durations on the order of two weeks which would

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generate higher or lower amplitude behavior in monthly averaged data) between 1950 and 1985 will not be captured by the model.

11.4.3. River flows

River flow data, recorded as average flow on a daily basis in $ft^3 \cdot s^{-1}$ was found on the USGS web sites for surface water statistics on Maryland and Virginia (http://waterdata.usgs.gov/md/nwis/sw and http://waterdata.usgs.gov/va/nwis/sw). The daily values were averaged over each month to derive time series for the Choptank, James, Nanticoke, Patapsco, Patuxent, Potomac, Rappahannock, Susquehanna, and York rivers. River gages are placed at numerous locations on all these rivers, but many start after the period of interest, end before 2003, or are discontinuous. Gages were chosen therefore to be as close as possible to the river mouth, while maximising the percentage of time coverage for the purposes of the model, see the station description section for more information.

The only missing data in the time series were for the Patapsco, Patuxent, and Susquehanna rivers. In each case a correlation analysis was done to find the average monthly river flows (as an x value) from each of the other six rivers compared to predicted monthly averages for the three incomplete time series (as the resultant y value). For the Patapsco missing values were based on the Potomac river $Y = 0.0125 \cdot X + 40.78$; $r^2 = 0.439$. For the Patuxent river missing values were based on the Rapahannock river $Y = 0.01375 \cdot X + 127.83$; $r^2 = 0.725$. For the Susquehanna missing values were derived from the Potomac river $Y = 2.2859 \cdot X + 12229$; $r^2 = 0.664$.

The flow for the 'York' river is a result of adding flows from its two tributaries, the Pamunkey and Mattaponi rivers. Lastly, according to a USGS press release dated January 6,

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2004 (see http://md.water.usgs.gov/outreach/) of the rivers described in this data set, three (the Susquehanna, Potomac, and James) account for approximately 85% of the total fresh water input to the CB. Using the data at hand, the remaining six account for a further 10% leaving (based on long term medians of the data sets) implying that the flow time series here account for approximately 95% of all the fresh water input to the CB.

11.4.4. Total Nitrogen

Time series of total nitrogen were available for all of the rivers as well as for 40 stations in CB itself, see Figure 1 for station locations and Table 1 and 2 for latitude / longitude coordinates. All of these data sets were obtained from the online water quality database for the Chesapeake Bay Program (http://www.chesapeakebay.net/data/index.cfm). Monitoring data for all stations began in 1984 on a roughly biweekly basis and continues to the present. For the CB stations data were grouped by month and into two sets (above the pycnocline and below). All river stations were chosen to be representative of the river mouth (in some cases a so called ‘lower estuary’ station had to be used). Table 1 therefore also contains the ‘river mouth’ latitude / longitude coordinates. The river total nitrogen was grouped by month and did not account for depth.

For all total nitrogen time series data before 1984 was estimated based on averages for each month in the 1985 to 2003 period. As with the wind data the seasonal trends are captured by this approximation, but not anomalously high or low values. An important caveat is that there has yet to be a useful estimation method superposed upon the longer term estimated data to account for generally suspected long term Bay wide changes in nutrient input to the Bay due

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to urban and agricultural effects. Some rule needs to be developed to reflect these changes before 1984.

11.4.5. Chesapeake Bay hydrology

Data on CB hydrology was contributed by the NOAA CB office.

11.4.6. Biological oxygen demand

Some records were available for 5-day BOD but there does not appear to have been any coordinated effort to measure or catalogue.

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12. Tables

12.1. Questions

Table 1. A sub-sample of questions and issues to be addressed by the Chesapeake Bay EwE model as formulated at the October, 2001 workshop in Laurel MD. Listed to illustrate topics that the ecosystem model has been or can be used to address.

1. Can water quality (e.g., DO) be managed by top-down actions such as fishery regulations?
2. What is the role of forage fish in Chesapeake Bay ecosystem dynamics?
3. Are there too many striped bass in the Chesapeake Bay?
4. What is the relative importance of climate variation on fish populations versus that of harvesting pressure?
5. Can the crab stock be restored through fishery reductions and the use of protected areas?
6. Can the crab stock be increased by the 'control' of other mortality agents, particularly predators?
7. What are the consequences of a tenfold increase in the oyster population in the Chesapeake Bay?

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8. Can protected areas for oysters enhance abundance and aid in their restoration?

12.2. Bonzek

Table 2. Chesapeake Bay Multispecies Monitoring and Assessment Program, Christopher F. Bonzek, Virginia Institute of Marine Science. From Bonzek (2004).

Species Common Name	**Species Latin Name(s)**	**Management Plan Entity***
American eel	*Anguilla rostrata*	ASMFC, CBP
Atlantic croaker	*Micropogonias undulatus*	ASMFC, CBP
Atlantic menhaden	*Brevoortia tyrannus*	ASMFC
Sturgeon, Atlantic and shortnose	*Acipenser oxyrhynchus, A. brevirostrum*	ASMFC, CBP (Atlantic)
Bay anchovy	*Anchoa mitchilli*	No management plan
Black drum	*Pogonius cromis*	CBP
Black seabass	*Centropristis striata*	ASMFC, CBP, MAFMC
Blue crab	*Callinectes sapidus*	CBP
Bluefish	*Pomatomus saltatrix*	ASMFC, MAFMC, CBP
Butterfish	*Peprilus triacanthus*	MAFMC
Catfish (several closely related species)	*Ictaluridae*	No management plan
Dogfish and coastal sharks	*Elasmobranchii*	ASMFC, MAFMC
Killifishes (several)	*Fundulus*	No management plan
Gizzard shad	*Dorosoma cepedianum*	No management plan
Mackerel, king and Spanish (both)	*Scomberomorus cavallas, .S. maculatus*	ASMFC (Spanish), CBP
Red drum	*Sciaenops ocellatus*	ASMFC, CBP
River herring (alewife and blueback herring)	*Alosa pseudoharengus A. aestivalis*	ASMFC, CBP
Scup	*Stenotomus chrysops*	ASMFC, MAFMC
Spot	*Leiostomus xanthurus*	ASMFC, CBP
Shad (American and hickory)	*Alosa sapidissima A. mediocris*	ASMFC (American), CBP (both)
Spotted seatrout	*Cynoscion nebulosus*	ASMFC, CBP
Striped bass	*Morone saxatilis*	ASMFC, CBP
Summer flounder	*Paralichthys dentatus*	ASMFC, CBP, MAFMC
Tautog	*Tautoga onitis*	ASMFC, CBP
Threadfin shad	*Dorosoma petenense*	No management plan
Weakfish	*Cynoscion regalis*	ASMFC, CBP
White perch	*Morone Americana*	No management plan
Yellow perch	*Perca flavescens*	No management plan
Other species of possible interest:		
Cobia	*Rachycentron canadum*	No management plan
Horseshoe crab	*Limulus poytphemus*	ASMFC, CBP
Squid (long-finned & shortfinned)	*Illex illecebrosus Loligo pealei*	MAFMC

* ASMFC = Atlantic States Marine Fisheries Commission
CBP = Chesapeake Bay Program
MAFMC = Mid Atlantic Fishery Management Council

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12.3. Basic parameters

Table 3. Basic parameters for the 1950-ecosystem model. Values estimated by Ecopath are shown in *italics*.

	Group name	Trophic level	Biomass ($t \cdot km^{-2}$)	Prod. / biomass ($year^{-1}$)	Cons. / biomass ($year^{-1}$)	Ecotrophic efficiency	Prod. / cons.
1	Striped bass YOY	3.56	0.0133	1.800	23.077	0.141	0.078
2	Striped bass resident	3.51	1.300	0.600	4.792	0.528	0.125
3	Striped bass migratory	3.40	1.157	0.350	2.300	0.940	0.152
4	Bluefish YOY	4.17	0.0161	5.650	18.111	0.009	0.312
5	Bluefish adult	4.05	0.240	0.589	3.300	0.770	0.178
6	Weakfish YOY	4.26	0.0257	4.000	13.525	0.159	0.296
7	Weakfish Adult	4.15	0.489	0.685	3.100	0.884	0.221
8	Atl. croaker	3.25	1.670	0.916	5.400	0.737	0.170
9	black drum	3.03	1.263	0.190	2.100	0.100	0.090
10	Summer flounder	3.66	0.454	0.520	2.900	0.950	0.179
11	Menhaden 0-1	2.99	16.444	1.500	15.860	0.082	0.095
12	Menhaden adult	2.10	30.000	0.800	7.800	0.836	0.103
13	Alewife and herring	3.13	3.537	0.750	9.400	0.950	0.080
14	American eel	3.38	0.957	0.250	2.500	0.800	0.100
15	Catfish	3.09	0.512	0.280	2.500	0.950	0.112
16	White perch YOY	3.55	0.00163	2.000	26.153	0.534	0.076
17	White perch adult	3.55	0.300	0.500	4.200	0.728	0.119
18	Spot	2.86	1.316	1.000	5.800	0.900	0.172
19	American shad	3.04	0.400	0.750	3.500	0.610	0.214
20	bay anchovy	3.41	3.400	3.000	10.900	0.283	0.275
21	Other flatfish	2.99	0.0460	0.460	4.900	0.950	0.094
22	gizzard shad	2.43	0.664	0.530	14.500	0.950	0.037
23	reef assoc. fish	3.40	0.178	0.510	3.100	0.900	0.165
24	non reef assoc. fish	3.05	0.932	1.000	5.000	0.900	0.200
25	Littoral forage fish	2.85	3.349	0.800	4.000	0.950	0.200
26	sandbar shark	4.05	0.0240	0.230	1.400	0.217	0.164
27	other elasmobranchs	3.33	0.500	0.150	0.938	0.112	0.160
28	Piscivorous birds	3.96	0.0300	0.163	150.600	0.000	0.001
29	Non-piscivorous seabirds	2.73	0.121	0.511	365.000	0.000	0.001
30	Blue crab YOY	2.80	1.580	5.000	12.057	0.699	0.415
31	Blue crab adult	3.09	4.000	1.000	4.000	0.877	0.250
32	Oyster YOY	2.00	2.445	6.000	9.087	0.124	0.660
33	Oyster 1+	2.09	20.400	0.150	2.000	0.214	0.075
34	soft clam	2.09	7.056	0.450	2.250	0.950	0.200
35	Hard clam	2.00	4.200	1.020	5.100	0.662	0.200

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36	ctenophores	3.48	3.400	8.800	35.200	0.205	0.250
37	sea nettles	4.13	0.583	5.000	20.000	0.000	0.250
38	Microzooplankton	2.00	6.104	140.000	350.000	0.950	0.400
39	Mesozooplankton	2.72	10.300	25.000	83.333	0.866	0.300
40	other suspension feeders	2.00	5.461	2.000	8.000	0.834	0.250
41	Other in/epi fauna	2.10	61.551	1.000	5.000	0.900	0.200
42	benthic algae	1.00	1.647	80.000	-	0.900	-
43	SAV	1.00	8.799	5.110	-	0.168	-
44	Phytoplankton	1.00	27.000	160.000	-	0.670	-
45	Detritus	3.56	1.000	-	-	0.028	-

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12.4. Catches

Table 4. Estimated catches (t · km^{2} · year^{-1}) for the Chesapeake Bay since 1950. Estimated from a variety of sources as described in the text. The SRA-row indicates which of the catch series that have been used (+) for stock reduction analysis within Ecosim. Values in the first column are years.

Group	SB res.	SB mig.	Blue-fish	Weak-fish	Atl. croa-ker	Black drum	Summer flounder	Men-haden ASMFC	Men-haden CB 12	Alewife	Eel	Catfish	White perch	Spot	Shad	Blue crab	Oyster	Soft clam	Hard clam 35
Group no.	2	3	5	7	8	9	10	12		13	14	15	17	18	19	31	33	34	
SRA					+	+	+			+	+	+	+		+				
1950	0.463	0.427	0.116	0.286	0.542	0.024	0.209	12.71	7.8	1.577	0.065	0.091	0.0727	0.456	0.203	4.31	1.36	0.073	0.071
1951	0.329	0.303	0.073	0.137	0.358	0.026	0.212	13.95	5.8	1.789	0.056	0.079	0.0643	0.508	0.22	3.84	1.34	0.011	0.067
1952	0.271	0.250	0.071	0.111	0.265	0.016	0.194	16.76	4.2	1.513	0.055	0.091	0.0581	0.619	0.256	3.46	1.56	0.126	0.059
1953	0.247	0.228	0.062	0.142	0.267	0.023	0.273	22.84	7.4	1.299	0.045	0.11	0.0528	0.407	0.204	3.47	1.68	0.011	0.045
1954	0.243	0.224	0.076	0.148	0.356	0.151	0.304	24.25	13.1	1.448	0.036	0.135	0.0557	0.452	0.212	2.92	1.89	0.059	0.037
1955	0.275	0.254	0.079	0.264	0.676	0.043	0.255	24.71	14.3	1.225	0.04	0.156	0.0563	0.416	0.225	2.47	1.78	0.128	0.043
1956	0.250	0.230	0.09	0.232	0.673	0.060	0.292	28.46	8.6	1.234	0.041	0.154	0.0604	0.333	0.24	2.73	1.68	0.126	0.042
1957	0.221	0.204	0.079	0.147	0.92	0.048	0.26	23.75	12.1	1.006	0.035	0.148	0.0508	0.382	0.239	3.11	1.58	0.178	0.050
1958	0.351	0.324	0.052	0.11	0.738	0.021	0.02	20.33	14.6	1.032	0.037	0.14	0.0561	0.547	0.188	2.62	1.7	0.205	0.045
1959	0.512	0.472	0.059	0.049	0.501	0.091	0.012	26.35	18.8	0.995	0.037	0.168	0.0727	0.356	0.148	2.38	1.51	0.253	0.088
1960	0.531	0.490	0.039	0.067	0.266	0.063	0.013	21.13	11.3	0.862	0.018	0.161	0.0555	0.405	0.122	3.74	1.23	0.213	0.083
1961	0.576	0.532	0.087	0.091	0.185	0.088	0.004	23.04	13.5	0.816	0.017	0.132	0.068	0.109	0.143	3.96	1.25	0.307	0.105
1962	0.470	0.434	0.163	0.105	0.077	0.127	0.002	21.4	14.9	1.218	0.015	0.124	0.0952	0.215	0.172	4.61	0.9	0.311	0.094
1963	0.516	0.476	0.187	0.074	0.007	0.124	0.002	13.7	11.7	1.251	0.026	0.092	0.0667	0.134	0.142	3.50	0.83	0.370	0.117
1964	0.412	0.380	0.112	0.11	0.023	0.025	0.001	10.28	15.3	1.269	0.023	0.084	0.0352	0.288	0.161	4.12	1	0.357	0.126
1965	0.410	0.378	0.059	0.14	0.09	0.038	0.001	10.42	16.3	1.746	0.043	0.06	0.0683	0.155	0.195	4.51	0.96	0.336	0.124
1966	0.488	0.451	0.072	0.074	0.086	0.170	0.001	7.89	12.6	1.363	0.031	0.069	0.0911	0.102	0.162	5.77	0.96	0.238	0.092
1967	0.462	0.427	0.038	0.043	0.019	0.074	0.001	7.72	10.1	1.431	0.044	0.06	0.0637	0.392	0.136	4.73	1.17	0.253	0.098
1968	0.488	0.450	0.106	0.079	0	0.124	0.001	8.98	12.4	1.648	0.044	0.064	0.0846	0.1	0.159	3.19	1.03	0.359	0.109

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1969	0.616	0.568	0.077	0.065	0.004	0.040	0.001	6.04	8.2	1.540	0.049	0.072	0.1043	0.092	0.161	3.46	1.01	0.282	0.122
1970	0.457	0.422	0.199	0.153	0.008	0.028	0.002	10.33	20.4	0.958	0.068	0.061	0.0749	0.547	0.234	3.85	1.12	0.272	0.086
1971	0.315	0.290	0.209	0.17	0.016	0.036	0.001	9.85	18.1	0.705	0.066	0.081	0.0765	0.044	0.112	4.27	1.16	0.088	0.098
1972	0.467	0.431	0.354	0.182	0.029	0.009	0.001	14.59	25.2	0.582	0.033	0.089	0.054	0.252	0.137	4.07	1.09	0.030	0.069
1973	0.624	0.576	0.884	0.35	0.082	0.004	0.001	13.79	22.9	0.516	0.02	0.069	0.0387	0.215	0.138	3.17	1.15	0.095	0.065
1974	0.481	0.444	1.027	0.216	0.096	0.012	0.001	11.32	17.5	0.686	0.073	0.08	0.0262	0.188	0.081	3.57	1.13	0.057	0.068
1975	0.336	0.310	0.99	0.309	0.316	0.013	0.001	9.77	14.6	0.552	0.068	0.081	0.0269	0.164	0.06	3.24	1.03	0.079	0.053
1976	0.226	0.209	1.301	0.274	0.411	0.011	0.001	13.42	20.2	0.200	0.033	0.066	0.0234	0.097	0.046	2.62	0.95	0.075	0.042
1977	0.210	0.194	1.027	0.283	0.548	0.006	0.001	13.34	23.1	0.068	0.025	0.089	0.0323	0.151	0.07	3.27	0.82	0.157	0.048
1978	0.136	0.125	0.852	0.274	0.513	0.016	0.001	13.33	19.4	0.106	0.062	0.068	0.0476	0.256	0.06	2.99	1.02	0.131	0.024
1979	0.112	0.104	0.941	0.428	0.132	0.012	0.001	13.74	20.9	0.083	0.067	0.069	0.0325	0.2	0.046	4.07	0.98	0.087	0.029
1980	0.207	0.191	0.904	0.423	0.042	0.002	0.002	15.99	24.8	0.062	0.034	0.103	0.0431	0.14	0.045	3.42	1.03	0.071	0.036
1981	0.162	0.149	0.623	0.175	0.022	0.021	0.001	14.35	18.7	0.028	0.067	0.08	0.0306	0.091	0.023	5.77	0.98	0.072	0.053
1982	0.031	0.029	0.571	0.155	0.007	0.017	0.001	15.15	27.6	0.064	0.036	0.08	0.03	0.064	0.027	4.98	0.79	0.089	0.032
1983	0.034	0.032	0.824	0.226	0.008	0.026	0.001	15.74	29.5	0.091	0.036	0.088	0.0247	0.131	0.028	5.49	0.53	0.043	0.053
1984	0.057	0.053	0.466	0.15	0.051	0.020	0.001	11.92	22.3	0.063	0.041	0.079	0.0306	0.046	0.061	5.48	0.56	0.060	0.034
1985	0.016	0.015	0.776	0.144	0.101	0.011	0.001	11.74	29.3	0.028	0.04	0.088	0.0194	0.13	0.037	5.53	0.6	0.048	0.033
1986	0.007	0.007	0.796	0.156	0.163	0.071	0.001	9.43	20.5	0.052	0.038	0.115	0.0212	0.131	0.032	4.75	0.62	0.159	0.042
1987	0.011	0.011	0.805	0.147	0.164	0.042	0.025	13.03	28.2	0.104	0.039	0.1	0.0189	0.266	0.037	4.23	0.39	0.198	0.046
1988	0.023	0.021	0.649	0.137	0.121	0.056	0.02	12.04	25.3	0.062	0.036	0.097	0.0302	0.127	0.041	4.44	0.24	0.183	0.059
1989	0.028	0.026	0.348	0.093	0.061	0.007	0.02	12.67	28.0	0.038	0.039	0.129	0.0265	0.172	0.05	4.93	0.2	0.097	0.069
1990	0.033	0.031	0.404	0.097	0.012	0.036	0.018	15.56	32.1	0.036	0.032	0.119	0.0339	0.123	0.039	5.70	0.2	0.077	0.071
1991	0.033	0.030	0.471	0.078	0.013	0.055	0.023	13.78	27.4	0.044	0.04	0.101	0.025	0.204	0.034	5.43	0.15	0.016	0.048
1992	0.061	0.056	0.235	0.05	0.065	0.050	0.021	11.41	26.2	0.085	0.04	0.099	0.0279	0.205	0.034	3.27	0.1	0.036	0.050
1993	0.085	0.079	0.24	0.067	0.329	0.027	0.03	12.67	29.1	0.080	0.045	0.107	0.0422	0.234	0.03	6.45	0.03	0.020	0.072
1994	0.112	0.104	0.208	0.084	0.394	0.057	0.209	10.33	23.4	0.058	0.043	0.14	0.0404	0.3	0.018	4.77	0.05	0.015	0.053
1995	0.188	0.174	0.19	0.089	0.44	0.025	0.212	13.54	32.0	0.019	0.032	0.105	0.052	0.233	0.007	4.35	0.07	0.014	0.043
1996	0.255	0.235	0.148	0.109	0.556	0.025	0.194	11.69	26.5	0.006	0.028	0.155	0.0587	0.2	0.011	4.30	0.05	0.011	0.036
1997	0.310	0.286	0.142	0.12	0.832	0.054	0.273	10.33	22.8	0.016	0.028	0.135	0.0875	0.23	0.024	4.92	0.08	0.010	0.031
1998	0.315	0.290	0.175	0.142	0.797	0.028	0.304	9.68	23.3	0.009	0.03	0.182	0.061	0.29	0.021	3.51	0.12	0.007	0.025
1999	0.295	0.273	0.114	0.125	0.834	0.024	0.255	6.59	17.4	0.009	0.029	0.169	0.0644	0.187	0.013	3.82	0.13	0.008	0.030
2000	0.436	0.403	0.142	0.126	0.89	0.022	0.292	6.61	16.9	0.009	0.025	0.138	0.0795	0.231	0.009	2.90	0.11	0.003	0.023
2001	0.403	0.372	0.181	0.092	0.954	0.022	0.26	9.29	22.3	0.013	0.025	0.162	0.0795	0.222	0.014	2.97	0.07	0.010	0.028
2002	0.467	0.431	0.147	0.083	0.858	0.011	0.02	6.71	16.8	0.015	0.018	0.147	0.0795	0.199	0.008	3.08	0.03	0.002	0.031
2003									17.2										

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12.5. *Striped bass growth parameters*

Table 5. Striped bass growth parameters.

Model group: Striped bass resident				
Growth parameters		*Stock assessment parameters*		
Linf	139	Parameter	Value	Estimated
K	0.117	Log_Ro	6.095	1
To	-1.126	compensation	14.24	2
A	9.99E-06	natural mortality (M)	0.15	-1
B	3.0851167	length @ 50% vulnerability	34.53	-1
Wm/Winf	0.2215559	shape	0.5	-1
Maturity ogive parameters		delta	0.309	3
length @ 50% mature (lh)	71.1			
shape (g)	0.25			

12.6. *Striped bass biomasses*

Table 6. Biomasses (relative) of striped bass in the Chesapeake Bay EwE model.

Resident striped bass includes year classes 1 to 6 (12 to 83 months of age).

Estimated from data in ASMFC (2003a).

Year	Young of year biomass	Resident biomass	Migratory biomass
1982	185	3690	2293
1983	586	3570	1925
1984	529	5306	2973
1985	195	5091	2909
1986	366	8551	2116
1987	679	11447	3048
1988	1432	15562	3064
1989	807	19014	6280
1990	636	20537	8548
1991	1518	24407	12860
1992	731	28354	14393
1993	622	34141	17929
1994	3114	43587	20859
1995	3024	45656	24614

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1996	1489	57632	33920
1997	1366	52344	28690
1998	1054	55402	30038
1999	1228	56180	29295
2000	866	63586	40178
2001	1958	46825	34950
2002	13882	44382	31939

12.7. Striped bass fishing mortality

Table 7. Fishing mortality estimates, 1983-2000 for striped bass in the Chesapeake Bay, based on ASMFC (Desfosse *et al.*, 2001). F-values are assumed for the period prior to 1982.

Year	F, Resident	F, Migratory
1950	0.356	0.343
1951	0.356	0.343
1952	0.356	0.343
1953	0.356	0.343
1954	0.356	0.343
1955	0.356	0.343
1956	0.356	0.343
1957	0.356	0.343
1958	0.356	0.343
1959	0.356	0.343
1960	0.356	0.350
1961	0.356	0.380
1962	0.356	0.410
1963	0.356	0.430
1964	0.356	0.460
1965	0.356	0.490
1966	0.356	0.510
1967	0.356	0.540
1968	0.356	0.570
1969	0.356	0.590
1970	0.5	0.610
1971	0.5	0.610
1972	0.5	0.610
1973	0.5	0.610
1974	0.5	0.610
1975	0.5	0.600
1976	0.5	0.570
1977	0.5	0.540

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1978	0.356	0.510
1979	0.356	0.245
1980	0.356	0.245
1981	0.356	0.245
1982	0.245	0.245
1983	0.303	0.162
1984	0.3	0.092
1985	0.1	0.121
1986	0.078	0.113
1987	0.035	0.070
1988	0.043	0.140
1989	0.04	0.092
1990	0.073	0.174
1991	0.063	0.196
1992	0.05	0.168
1993	0.043	0.239
1994	0.07	0.208
1995	0.098	0.227
1996	0.13	0.256
1997	0.143	0.290
1998	0.2	0.320
1999	0.178	0.330
2000	0.208	0.353

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12.8. *Commercial fish diet compositions*

Table 8. Diet compositions for high trophic level, multi-stanza, commercial fish in the Chesapeake Bay 1950-ecosystem model. Diet compositions are expressed as proportions, and are expressed on a volume or wet weight basis. See text for sources.

	Prey \ Predator	Striped bass YOY	Striped bass resident	Striped bass migratory	Blue-fish YOY	Blue-fish adult	Weak-fish YOY	Weak-fish adult	White perch YOY	White perch adult
1	Striped bass YOY			0.0005				0.0005		
6	Weakfish YOY		0.00086		0.001					
7	Weakfish Adult		0.001	0.001						
8	Atl. Croaker		0.01	0.102		0.077	0.131	0.035		
10	Summer flounder							0.01		
11	Menhaden YOY		0.086		0.14	0.48		0.464		
12	Menhaden adult		0.442	0.685						
13	Alewife and herring		0.095	0.124						
14	American eel		0.013							
16	White perch YOY	0.001								
17	White perch adult		0.005	0.002						
18	Spot		0.068	0.011	0.014	0.224		0.031		
19	American shad									
20	bay anchovy	0.105	0.009	0.011	0.545	0.168	0.768	0.429		0.167
22	gizzard shad			0.028						
23	reef assoc. fish		0.008							0.016
24	non reef assoc. fish		0.086			0.022				
25	Littoral forage fish	0.321	0.06		0.286	0.028			0.022	0.146
30	Blue crab YOY		0.003	0.023						
39	Mesozooplankton	0.124							0.550	0.167
40	other suspension feeders		0.059							
41	Other in/epi fauna	0.449	0.055	0.012	0.014		0.101	0.031	0.221	0.504
46	Import								0.208	

12.9. *Bluefish growth parameters*

Table 9. Growth and maturity parameters used in the single species stock assessment, as well as, ratio of weight at maturity and asymptotic weight used in multi-stanza calculations.

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Estimated parameter values from the stock assessment model are listed on the right; (positive phase values indicate parameter was estimated by fitting the model to time series data; negative values indicate parameter was fixed).

Model Group: Bluefish				
Growth Parameters		*Stock assessment parameters*		
		Parameter	Value	Estimated
Linf (cm)	87.2	Log_Ro	7.729	1
K ($^{year-1}$)	0.26	compensation	5.84	2
T_0 (year)	-0.93	natural mortality (M)	0.26	-1
A	1.09E-05	length @ 50% vulnerability	34	-1
B	3.0548	shape	0.5	-1
Wm/Winf	0.2007328			
Maturity Ojive Parameters		delta	0.01	3
length @ 50% mature (lh)	35.433408			
shape (g)	0.3544103			

12.10. Bluefish biomass and F

Table 10. Bluefish biomass (B, relative), fishing mortality (F, year^{-1}) and young of the year biomass (YOY, t·km^{-2}) used in the Chesapeake Bay EwE model.

Time Series Data							Single species assessment		
Year	Commercial landings (t·km^{-2})	Recreational landings (t·km^{-2})	Total landings (t·km^{-2})	Lee (2003) kg/tow	Lee (2003) N/tow	Atlantic Survey	Bt (t·km^{-2})	F	YoY Bt
1950	0.019	0.097	0.116				0.240	0.483	0.010
1951	0.012	0.061	0.073				0.153	0.481	0.010
1952	0.012	0.059	0.071				0.129	0.551	0.054
1953	0.010	0.051	0.062				0.150	0.409	0.035
1954	0.012	0.064	0.076				0.171	0.446	0.028
1955	0.013	0.066	0.079				0.174	0.451	0.033
1956	0.015	0.076	0.090				0.181	0.499	0.038
1957	0.013	0.066	0.079				0.185	0.429	0.039
1958	0.009	0.044	0.052				0.200	0.261	0.040
1959	0.010	0.049	0.059				0.244	0.242	0.041
1960	0.006	0.033	0.039				0.286	0.136	0.044
1961	0.014	0.073	0.087				0.358	0.242	0.053
1962	0.027	0.137	0.163				0.403	0.405	0.062
1963	0.031	0.157	0.187				0.403	0.465	0.077
1964	0.018	0.093	0.112				0.407	0.274	0.086
1965	0.010	0.049	0.059				0.491	0.120	0.086

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1966	0.012	0.060	0.072				0.639	0.112	0.086
1967	0.006	0.032	0.038				0.791	0.048	0.103
1968	0.017	0.089	0.106				1.012	0.105	0.131
1969	0.013	0.065	0.077				1.217	0.063	0.158
1970	0.032	0.166	0.199				1.515	0.131	0.195
1971	0.034	0.175	0.209				1.765	0.118	0.226
1972	0.058	0.296	0.354	0.07	0.10		2.081	0.170	0.269
1973	0.144	0.740	0.884	0.43	0.29		2.343	0.377	0.301
1974	0.168	0.860	1.027	1.46	1.15	71	2.225	0.462	0.339
1975	0.162	0.829	0.990	5.59	1.68	75	2.065	0.479	0.368
1976	0.212	1.089	1.301	5.75	5.15	83	1.980	0.657	0.354
1977	0.168	0.859	1.027	6.54	6.78	92	1.674	0.613	0.335
1978	0.139	0.713	0.852	5.87	1.70	100	1.535	0.555	0.325
1979	0.153	0.787	0.941	7.43	5.32	108	1.492	0.630	0.287
1980	0.148	0.757	0.904	7.07	4.36	101	1.340	0.675	0.268
1981	0.125	0.498	0.623	13.18	12.49	92	1.183	0.526	0.263
1982	0.131	0.440	0.571	4.87	4.03	80	1.204	0.474	0.242
1983	0.084	0.740	0.824	3.96	2.47	75	1.234	0.667	0.219
1984	0.061	0.405	0.466	7.65	7.00	63	1.056	0.442	0.222
1985	0.098	0.678	0.776	3.48	2.09	62	1.131	0.686	0.227
1986	0.089	0.707	0.796	3.88	4.72	67	0.978	0.815	0.199
1987	0.070	0.735	0.805	2.71	0.91	50	0.795	1.013	0.211
1988	0.165	0.483	0.649	1.99	3.55	37	0.616	1.054	0.187
1989	0.047	0.301	0.348	9.18	10.67	30	0.497	0.702	0.156
1990	0.062	0.341	0.404	2.54	1.10	27	0.515	0.784	0.124
1991	0.048	0.423	0.471	2.04	1.82	26	0.453	1.041	0.102
1992	0.036	0.198	0.235	1.37	2.09	20	0.332	0.707	0.106
1993	0.036	0.205	0.240	0.72	0.26	17	0.347	0.692	0.095
1994	0.036	0.172	0.208	1.68	1.44	15	0.338	0.616	0.070
1995	0.029	0.161	0.190	2.04	1.05	15	0.326	0.584	0.074
1996	0.028	0.120	0.148	2.30	1.27	15	0.324	0.458	0.072
1997	0.034	0.109	0.142	1.39	0.65	16	0.352	0.404	0.070
1998	0.044	0.131	0.175	1.32	1.27	18	0.383	0.457	0.070
1999	0.029	0.085	0.114	2.73	2.88	23	0.390	0.291	0.075
2000	0.028	0.114	0.142	1.08	0.55	36	0.458	0.310	0.082
2001	0.042	0.140	0.181	1.68	2.25		0.514	0.353	0.083
2002	0.027	0.121	0.147	1.75	2.16		0.546	0.270	0.096

12.11. *Weakfish growth parameters*

Table 11. Weakfish growth parameters

Model Group: Weakfish				
Growth Parameters		*Stock assessment parameters*		
		Parameter	Value	Estimated
Linf	68.6			
K	0.35	Log_Ro	6.095	1

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To	-0.051	compensation	14.24	2
A	1.10E-05	natural mortality (M)	0.25	-1
B	2.9575	length @ 50% vulnerability	34.53	-1
Wm/Winf	0.1382508	shape	0.5	-1
Maturity Ojive Parameters		delta	0.309	3
length @ 50% mature (lh)	25			
shape (g)	1			

12.12. Weak fish B

Table 12. Weakfish assessment. See text for details.

	Time Series Data					Single species assessment	
Year	Total landings ($t \cdot km^{-2}$)	VPA SSB Weakfish	VIMS River Survey (age 0)	Meat Wt in Recreation Fishery	VIMS River & Bay (age 0)	B_t ($t \cdot km^{-2}$)	F
1950	0.286					0.489	0.585
1951	0.137					0.290	0.473
1952	0.111					0.212	0.524
1953	0.142					0.201	0.707
1954	0.148					0.220	0.671
1955	0.264					0.232	1.140
1956	0.232					0.174	1.331
1957	0.147					0.142	1.035
1958	0.110					0.156	0.707
1959	0.049					0.190	0.258
1960	0.067					0.270	0.248
1961	0.091					0.332	0.274
1962	0.105					0.372	0.282
1963	0.074					0.402	0.184
1964	0.110					0.465	0.237
1965	0.140					0.501	0.279
1966	0.074					0.513	0.144
1967	0.043					0.582	0.074
1968	0.079					0.681	0.116
1969	0.065					0.739	0.088
1970	0.153					0.803	0.191
1971	0.170					0.783	0.217
1972	0.182					0.751	0.243
1973	0.350					0.714	0.490
1974	0.216					0.565	0.383
1975	0.309					0.523	0.591
1976	0.274					0.428	0.640

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1977	0.283					0.365	0.776
1978	0.274					0.302	0.907
1979	0.428		7.20			0.250	1.709
1980	0.423		9.90			0.147	2.878
1981	0.175		6.10			0.084	2.080
1982	0.155	12254	10.90	2.03		0.095	1.625
1983	0.226	10825	10.80	0.95		0.105	2.153
1984	0.150	8722	6.10	0.91		0.076	1.973
1985	0.144	11812	37.00	1.03		0.073	1.983
1986	0.156	20805	4.60	0.54		0.073	2.126
1987	0.147	19263	17.80	0.63		0.066	2.239
1988	0.137	12409	21.80	0.51	8.9	0.059	2.337
1989	0.093	8307	21.30	0.66	12.2	0.056	1.659
1990	0.097	9001	30.00	0.50	4.8	0.067	1.440
1991	0.078	10562	15.30	0.54	3.6	0.073	1.068
1992	0.050	9574	15.90	0.66	6.9	0.086	0.580
1993	0.067	8884	15.40	0.47	6.1	0.120	0.558
1994	0.084	18693	7.00	0.45	2.7	0.146	0.575
1995	0.089	20396	11.00	0.53	6.1	0.162	0.549
1996	0.109	27134	7.40	0.59	7.8	0.182	0.600
1997	0.120	42038	14.80	0.60	7.1	0.196	0.611
1998	0.142	38116	9.90	0.77	8.2	0.209	0.678
1999	0.125	48980	16.30	0.87	7.4	0.212	0.590
2000	0.126	51598	11.10	0.90	9.4	0.230	0.549
2001	0.092		11.40		5.1	0.249	0.369
2002	0.083		8.60		6.3	0.297	0.279

12.13. Diets for other commercial fish

Table 13. Diets for other commercial fish species. Diets are expressed as proportions.

	Prey \ Predator	Atl. croaker	Black drum	Summer flounder	Menhaden YOY	Menhaden adult	Alewife and herring	American eel	Catfish	Spot	American shad
1	SB YOY	0.0001									
4	Bluefish YOY			0.001							
6	Weakfish YOY			0.01				0.001			
8	Atl. croaker			0.057							
16	White perch YOY								0.001		
18	Spot			0.074							
20	Bay anchovy	0.05		0.158							
22	gizzard shad								0.111		
24	non reef assoc. fish			0.214							
25	Littoral	0.035						0.1			

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	forage fish										
30	Blue crab YOY	0.05						0.147			
32	Oyster YOY		0.053								
34	soft clam		0.386					0.05			
35	Hard clam		0.135					0.01			
38	Micro zooplankton	0.014			0.3	0.101	0.25				0.13
39	Meso zooplankton	0.079			0.4		0.25				0.13
40	other suspension feeders	0.062	0.426					0.154	0.444		
41	Other in/ epi fauna	0.1		0.487				0.4	0.444	0.778	0.31
42	benthic algae					0.012					
43	SAV	0.005									
44	Phytoplankton				0.3	0.887	0.1				
45	Detritus	0.082								0.222	0.1
46	Import	0.522					0.4	0.038			0.33

12.14. Atlantic croaker recruitment

Table 14. Estimates of recruitment for Atlantic croaker from VIMS spring and fall trawl series. The mean is estimated as the mean of the fall and spring values after each series has been standardized to its mean.

Year	Spring	Fall	Mean
1978	2.1		
1979	1.8	4.7	0.31
1980	0.2	2.5	0.08
1981	1.2	2.9	0.20
1982	9.5	3.2	1.10
1983	1.2	7.3	0.31
1984	4.1	45.8	1.59
1985	3.2	75	2.22
1986	5.5	12.6	0.91
1987	2.2	6.5	0.40
1988	4.6	9.1	0.72
1989	3	64.8	1.95
1990	12.9	13.1	1.72
1991	10.3	9.6	1.35
1992	19.4	14.6	2.46
1993	3	5.4	0.46
1994	5.5	13.5	0.93

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1995	0.4	11.8	0.34
1996	7.8	31.1	1.62
1997	6.2	10.4	0.93
1998	4.1	21.3	0.98
1999	1.4	14.3	0.51
2000	1.2	6	0.28
2001	4.8	7	0.69
2002	0.3	10.4	0.29
2003		96.2	

12.15. Summer flounder biomass

Table 15. Summer flounder biomass estimate, Atlantic coast wide (NEFSC, 2002).

1982	41939
1983	48802
1984	44553
1985	40196
1986	38453
1987	35403
1988	29412
1989	16122
1990	16449
1991	17102
1992	17647
1993	21351
1994	28214
1995	35948
1996	36928
1997	32244
1998	37800
1999	36275
2000	36819
2001	43137

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12.16. Menhaden biomass and F

Table 16. Estimates of biomass (relative values), and F for menhaden, age group 1+ calculated from information in ASMFC (2004). F-estimates for the years prior to 1955 (*italics*) are estimated from the catch ratio in the year relative to the catch in 1955 times the 1955-F.

Year	F (year^{-1})	Biomass
1950	*0.306*	
1951	*0.336*	
1952	*0.403*	
1953	*0.549*	
1954	*0.583*	
1955	0.594	1040
1956	0.791	899
1957	0.586	1013
1958	0.591	860
1959	0.369	1785
1960	0.396	1332
1961	0.502	1146
1962	0.672	796
1963	0.746	459
1964	0.76	338
1965	0.872	299
1966	0.748	264
1967	0.541	357
1968	0.71	316
1969	0.407	371
1970	0.542	477
1971	0.511	482
1972	0.726	502
1973	0.659	524
1974	0.648	437
1975	0.594	411
1976	0.645	520
1977	0.622	536
1978	0.626	532
1979	0.61	563
1980	0.618	646
1981	0.627	572
1982	0.532	713

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1983	0.717	548
1984	0.655	455
1985	0.489	600
1986	0.368	640
1987	0.435	749
1988	0.541	556
1989	0.462	685
1990	0.539	722
1991	0.526	655
1992	0.435	656
1993	0.364	869
1994	0.414	624
1995	0.476	711
1996	0.468	625
1997	0.483	534
1998	0.506	478
1999	0.416	396
2000	0.381	433
2001	0.432	538
2002	0.41	409

12.17. Alewife and American shad from fish lifts

Table 17. Annual catch of adult shad and river herring in the Conowingo Dam fish lifts, Susquehanna River, MD, 1972-2004 (St. Pierre, Pers. comm.).

Year	Am. shad	Hick. shad	Blueback herring	Alewife
1972	185	429	58,198	10,345
1973	65	739	330,341	144,727
1974	121	219	340,084	16,675
1975	87	20	69,916	4,311
1976	82	0	35,519	235
1977	165	1	24,395	188
1978	54	0	13,098	5
1979	50	0	2,282	9
1980	139	1	502	9
1981	328	1	618	129
1982	2,039	15	25,249	3,433
1983	413	5	517	50
1984	167	6	311	26
1985	1,546	9	6,763	379
1986	5,195	45	6,327	2,822
1987	7,667	35	5,861	357
1988	5,146	64	14,570	674
1989	8,218	28	3,598	1,902
1990	15,719	77	9,658	425

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1991	27,227	120	15,616	2,649
1992	25,721	376	27,533	3,344
1993	13,546	0	8,626	572
1994	32,330	1	2,851	75
1995	61,650	37	97,863	5,575
1996	37,513	0	1,132	4
1997	103,945	118	376,072	74
1998	46,481	6	6,211	37
1999	69,370	32	138,625	1,811
2000	163,331	1	29,289	9,190
2001	204,554	36	301,240	15,282
2002	117,348	6	2,465	215
2003	134,937	1	713	37
2004	112,786	0	102	89

Notes: All catch data prior to 1991 are the West lift (trap) only. The East fish lift began operations in 1991 and operated in trap and transfer mode through 1996. Thereafter, all fish from the East lift were passed over the dam. Most American shad are currently taken in the East lift and most river herring and hickory shad typically come from the West lift.

12.18. White perch recruitment series

Table 18. White perch abundance indices for 'upper rivers' from the VIMS Trawl Surveys.

Year\Age	0	1+
1978		3.3
1979		15.8
1980		18.9
1981		15.9
1982		26.6
1983	10	23.8
1984	13.3	36.8
1985	1.9	9.5
1986	1.8	21.9
1987	42.1	35.1
1988	5.3	25.9
1989	13.3	32
1990	3.3	29.5

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1991	2.3	15.8
1992	1.2	15
1993	17.9	18.8
1994	8.4	40.8
1995	4.6	12.5
1996	20.6	20.2
1997	10	27.4
1998	7.1	22.2
1999	16.1	16.8
2000	6	17.1
2001	9.48	20.6
2002	9.16	18.5

12.19. White perch biomass and F

Table 19. White perch abundance estimates and fishing mortality (F, $year^{-1}$). Fishing mortality is assumed constant at 0.27 $year^{-1}$ for the years 1950-1978.

Year	Young of year	Age 1+	Rel. B.	F
1979		3.3		0.27
1980		15.8		0.27
1981		18.9	3.27	0.27
1982		15.9	3.38	0.28
1983	10.0	26.6	3.46	0.22
1984	13.3	23.8	3.73	0.30
1985	1.9	36.8	3.75	0.23
1986	1.8	9.5	4.12	0.25
1987	42.1	21.9	4.40	0.25
1988	5.3	35.1	4.71	0.30
1989	13.3	25.9	4.85	0.19
1990	3.3	32.0	5.52	0.25
1991	2.3	29.5	5.88	0.24
1992	1.2	15.8	6.39	0.20
1993	17.9	15.0	7.11	0.28
1994	8.4	18.8	7.19	0.27
1995	4.6	40.8	7.27	0.23
1996	20.6	12.5	7.63	0.30
1997	10.0	20.2	7.43	0.49
1998	7.1	27.4	6.00	0.36
1999	16.1	22.2	5.57	0.36
2000	6.0	16.8	5.12	0.63

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12.20. Spot

Table 20. Catches of spot in the Chesapeake Bay. Recreational (rec.) and commercial catches (in pounds, #) for 1981-2000 are from ASFMC (ASMFC, 1998). The ratio between recreational and commercial catches is then extrapolated to earlier and later years assuming a linear trend in the ratio. Commercial catches ($t \cdot km^{-2} \cdot year^{-1}$) for 1950 – 2002 are from the NOAA Fisheries Statistics and Economics Division online database (http://www.st.nmfs.gov), while the recreational catches are estimated from the rec./com. ratio and the commercial catch.

Year	Rec. (#)	Com. (#)	Rec./com. ratio	Com ($t \cdot km^{-2} \cdot year^{-1}$)	Rec. ($t \cdot km^{-2} \cdot year^{-1}$)	Total ($t \cdot km^{-2} \cdot year^{-1}$)
1950			1.19	0.209	0.247	0.456
1951			1.17	0.234	0.274	0.508
1952			1.15	0.287	0.332	0.619
1953			1.14	0.190	0.217	0.407
1954			1.12	0.213	0.239	0.452
1955			1.11	0.198	0.219	0.416
1956			1.09	0.159	0.174	0.333
1957			1.08	0.184	0.198	0.382
1958			1.06	0.265	0.281	0.547
1959			1.04	0.174	0.182	0.356
1960			1.03	0.200	0.206	0.405
1961			1.01	0.054	0.055	0.109
1962			1.00	0.108	0.108	0.215
1963			0.98	0.068	0.066	0.134
1964			0.97	0.147	0.142	0.288
1965			0.95	0.079	0.075	0.155
1966			0.93	0.052	0.049	0.102
1967			0.92	0.204	0.188	0.392
1968			0.90	0.053	0.048	0.100
1969			0.89	0.049	0.043	0.092
1970			0.87	0.292	0.255	0.547
1971			0.86	0.024	0.020	0.044
1972			0.84	0.137	0.115	0.252
1973			0.82	0.118	0.097	0.215
1974			0.81	0.104	0.084	0.188
1975			0.79	0.092	0.073	0.164
1976			0.78	0.055	0.043	0.097
1977			0.76	0.085	0.065	0.151
1978			0.75	0.147	0.110	0.256

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1979			0.73	0.116	0.085	0.200
1980			0.72	0.082	0.058	0.140
1981	6915818	7502660	0.92	0.047	0.043	0.091
1982	3986818	10440456	0.38	0.046	0.018	0.064
1983	4998290	7156787	0.70	0.077	0.054	0.131
1984	1799940	5899237	0.31	0.035	0.011	0.046
1985	5944428	7175456	0.83	0.071	0.059	0.130
1986	3393314	6965468	0.49	0.088	0.043	0.131
1987	3846868	8100735	0.47	0.180	0.086	0.266
1988	2522408	6885199	0.37	0.093	0.034	0.127
1989	3293815	7052045	0.47	0.117	0.055	0.172
1990	3584905	6563745	0.55	0.080	0.044	0.123
1991	4514386	7176937	0.63	0.125	0.079	0.204
1992	4024450	6765078	0.59	0.128	0.076	0.205
1993	3371427	7315567	0.46	0.160	0.074	0.234
1994	4327879	8795939	0.49	0.201	0.099	0.300
1995	3118944	7489478	0.42	0.164	0.068	0.233
1996	2036103	5647298	0.36	0.147	0.053	0.200
1997	2717808	6570735	0.41	0.163	0.067	0.230
1998	3062028	7293919	0.42	0.204	0.086	0.290
1999	1652527	5583934	0.30	0.144	0.043	0.187
2000	2006623	6872122	0.29	0.179	0.052	0.231
2001			0.39	0.160	0.062	0.222
2002			0.37	0.145	0.054	0.199

12.21. Spot abundance

Table 21. Estimates of spot abundance from the VIMS trawl series is available for rivers and for rivers and bays for age group 0 and for age group 1+. We estimate an overall mean abundance from the four series based on their standardized (to mean) values.

	River	River & Bay	River	River & Bay	Mean
Age	0	0	1+	1+	
1978			1.34		0.68
1979	17.3		1.14		0.73
1980	8.9		2.62		0.89
1981	31.1		3.74		1.75
1982	36.5		9.01		3.22
1983	21.5		0.92		0.79
1984	50.3		1.04		1.56
1985	19.6		1.25		0.82

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1986	26.3		1.96		1.17
1987	20.4		1.84	0.24	0.77
1988	50.2	67.5	4.87	1.11	2.93
1989	54.2	32.3	0.63	0.14	1.43
1990	53.1	44.6	1.92	0.65	2.00
1991	21.4	16.6	2.68	1.59	1.49
1992	4.4	2	0.57	0.31	0.28
1993	11.8	9.7	2.62	1.47	1.19
1994	8.9	9.1	1.53	0.73	0.74
1995	2.4	1.5	0.21	0.18	0.15
1996	4.8	4.5	0.85	0.51	0.44
1997	19.7	8.6	0.77	0.65	0.74
1998	3	1.9	1.3	0.42	0.39
1999	6.6	4	1.06	0.87	0.60
2000	4.9	2.7	0.87	0.94	0.56
2001	3.7	2.8			0.20
2002	3.1	2.1			0.16
2003	2.3	2.6			0.16

12.22. American shad

Table 22. Estimates of American shad relative abundance for the Upper Chesapeake Bay based on Schaefer population estimates, 1982-1996. Fishing mortality rates (F, year^{-1}) are coastal estimates from the Upper Chesapeake Bay (ASMFC, 1998). The estimates are not used for the Ecosim simulations due to uncertainty about how to extrapolate to the Bay overall.

Year	Population estimate	F
1980		0.23
1981		0.51
1982	33742	0.22
1983	8031	0.43
1984	3537	0.77
1985	12903	0.53
1986	19763	0.33
1987	29031	0.31
1988	52819	0.26
1989	78834	0.27
1990	144419	0.14
1991	181585	0.14

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1992	148829	0.14
1993	49193	0.26
1994	193127	0.07
1995	340016	0.02
1996	204642	0.04

12.23. Bay anchovy, juvenile b

Table 23. Estimate of relative abundance of juvenile bay anchovy. Based on Maryland DNR juvenile seine survey data presented at www.chesbay.org.

Year	Abundance
1958	0.46
1959	4.40
1960	1.19
1961	0.99
1962	1.92
1963	3.14
1964	1.98
1965	4.30
1966	7.67
1967	3.87
1968	3.21
1969	4.00
1970	1.09
1971	0.46
1972	1.88
1973	1.16
1974	4.96
1975	1.16
1976	1.19
1977	0.73
1978	0.66
1979	1.52
1980	0.86
1981	2.78
1982	1.29
1983	2.08
1984	1.65
1985	2.94
1986	2.74
1987	1.65
1988	0.83
1989	1.42
1990	2.02

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1991	3.31
1992	1.82
1993	1.82
1994	0.63
1995	0.40
1996	0.20
1997	0.13
1998	0.40
1999	0.66
2000	0.20
2001	0.26
2002	0.23
2003	0.60

12.24. Bay anchovy abundance, Virginia survey

Table 24. Geometric mean estimates of bay anchovy relative abundance from the Virginia juvenile trawl survey. The average is calculated based on standardized values (to the mean) for each series.

	Rivers	Rivers, bays	Rivers	Rivers & bays	
Year\Age	0	0	1+	1+	Average
1978			7.2		0.57
1979	1.6		26.4		1.09
1980	8.8		22.4		1.14
1981	12		13.8		0.89
1982	9.5		10.4		0.69
1983	12		19.8		1.13
1984	7.1		25.4		1.21
1985	14		9.2		0.77
1986	26.8		19.1		1.53
1987	54.1		22.1	12.9	2.08
1988	32.6	18.1	22.4	9.6	1.35
1989	22.7	51.6	7	5	1.12
1990	8.8	6.7	12.5	4.9	0.57
1991	33.4	22.8	9.8	13.7	1.27
1992	14.5	40.8	15.3	11.9	1.24

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1993	28.9	42.7	4.8	5.4	1.09
1994	19.8	14.4	9.9	15.4	1.03
1995	18.6	18.5	2.5	8.8	0.74
1996	5.1	16.9	8.9	11.6	0.72
1997	12.6	17.3	6.2	15.6	0.89
1998	9.7	31.1	6.7	7.7	0.79
1999	21.3	14.4	6.6	6	0.74
2000	16.2	40.4	3.7	5.5	0.86
2001	4.4	9.1			0.31

12.25. Diet compositions for other fish

Table 25. Diet compositions for other fish. Diets are expressed as proportions (sum = 1) and are evaluated on a weight or volume basis. For sources see text.

	Prey \ Predator	bay anchovy	Other flatfish	gizzard shad	reef assoc. fish	non reef assoc. fish	Littoral forage fish	sandbar shark	other elasmo-branchs
7	Weakfish Adult							0.04	
8	Atl. croaker							0.35	0.011
12	Menhaden adult							0.03	
13	Alewife and herring				0.05	0.05		0.01	
14	American eel							0.01	
18	Spot								0.034
20	bay anchovy				0.101				0.073
21	Other flatfish							0.06	
24	non reef assoc. fish								0.011
25	Littoral forage fish				0.07	0.05	0.015		
27	other elasmobranchs							0.25	
30	Blue crab YOY				0.1		0.04	0.05	
31	Blue crab adult				0.1			0.05	
38	Microzooplankton	0.365							
39	Mesozooplankton	0.562		0.25		0.05	0.041		
40	other suspension feeders		0.05		0.202	0.1			0.13
41	Other in/epi fauna	0.073	0.85		0.296	0.6	0.598	0.15	0.324
42	benthic algae				0.031				
43	SAV				0.05				
44	Phytoplankton			0.75					
45	Detritus		0.1			0.15	0.283		
46	Import						0.023		0.417

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12.26. Piscivorous birds

Table 26. List of piscivorous birds included in the Chesapeake Bay ecosystem model. Common names and scientific names are presented. Based on input from mesotrophic levels group in CB workshop 1 (October 22-24). (D. Forsell, pers. comm.)

Common Loon	*Gavia immer*
Red-throated Loon	*Gavia stellata*
Horned Grebe	*Podiceps auritus*
Red-necked Grebe	*Podiceps grisegena*
Northern Gannet	*Sula bassanus*
Brown Pelican	*Pelecanus occidentalis*
Double-crested Cormorant	*Phalacrocorax auritus*
Great Blue Heron	*Ardea herodias*
Great Egret	*Casmerodius albus*
Snowy Egret	*Egretta thula*
Little Blue Heron	*Egretta caerulea*
Tricolored Heron	*Egretta tricolor*
Yellow-crowned Night Heron	*Nyctanassa violaea*
Black-crowned Night Heron	*Nycticorax nycticorax*
Green Heron	*Butorides virescenes*
Brant	*Branta bernicla*
Canada Goose	*Branta canadensis*
Snow Goose	*Chen caerulescens*
Mute Swan	*Cygnus olor*
Tundra Swan	*Cygnus columbianus*
Wood Duck	*Aix sponsa*
Gadwall	*Anas stepera*
American Wigeon	*Anas americana*
American Black Duck	*Anas rubripes*
Mallard	*Anas platyrhynchos*
Blue-winged Teal	*Anas discors*
Northern Shoveler	*A. Clypeata*
Northern Pintail	*Anas acuta*
Green-winged Teal	*Anas crecca*
Canvasback	*Aythya valisineria*
Redhead	*Aythya americana*
Ring-necked Duck	*Aythya collaris*
Greater and Lesser Scaup	*Aythya marila A. affinis*
Surf Scoter	*Melanitta perspicillata*
White-winged Scoter	*Melanitta fusca*
Black Scoter	*Melanitta nigra*
Long-tailed Duck	*Clangula hyemalis*
Bufflehead	*Bucephala albeola*
Common Goldeneye	*Bucephala clangula*
Hooded Merganser	*Lophodytes cucullatus*
Common Merganser	*Mergus merganser*
Red-Breasted Merganser	*Mergus serrator*
Ruddy Duck	*Oxyura jamaicensis*
Bald Eagle	*Haliaeetus leucocephalus*
Osprey	*Pandion haliaetus*
American Coot	*Fulica americana*
American Oystercatcher	*Haematopus palliatus*
Laughing Gull	*Larus atricilla*
Bonaparte's Gull	*Larus philadelphia*
Ring-billed Gull	*Larus delawarensis*
Herring Gull	*Larus argentatus*
Great Black-backed Gull	*Larus marinus*
Black-legged Kittiwake	*Rissa tridactyla*
Royal Tern	*Sterna maxima*
Common Tern	*Sterna hirundo*
Least Tern	*Sterna antillarum*

Sandwich Tern	
Black Skimmer	*Rynchops niger*

12.27. Diets for birds

Table 27. Diets for piscivorous and non-piscivorous birds. Both diet compositions are based on general knowledge for the groups, and are expressed as proportions (wet weight or volume). Import includes food taken outside the Chesapeake Bay model area.

	Prey \ Predator	Piscivorous birds	Non-piscivorous seabirds
1	Striped bass YOY	0.0002	
2	Striped bass resident	0.0001	
6	Weakfish YOY	0.0001	
11	Menhaden YOY	0.026	
12	Menhaden adult	0.04	
13	Alewife and herring	0.05	
14	American eel	0.01	
15	Catfish	0.01	
20	bay anchovy	0.133	
21	Other flatfish	0.004	
22	gizzard shad	0.026	
25	Littoral forage fish	0.031	
30	Blue crab YOY	0.01	
35	Hard clam		0.01
38	Microzooplankton	0.001	
39	Mesozooplankton	0.095	
40	other suspension feeders		0.041
41	Other in/epi fauna		0.235
42	benthic algae		
43	SAV		0.128
45	Detritus		0.011
46	Import	0.563	0.575

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12.28. Non-piscivorous birds

Table 28. List of bird species (common name and scientific names given) included in the non-piscivorous group of the Chesapeake Bay ecosystem model.

Brant	*Branta bernicla*
Canada Goose	*Branta canadensis*
Snow Goose	*Chen caerulescens*
Mute Swan	*Cygnus olor*
Tundra Swan	*Cygnus columbianus*
Wood Duck	*Aix sponsa*
Gadwall	*Anas stepera*
American Wigeon	*Anas americana*
American Black Duck	*Anas rubripes*
Mallard	*Anas platyrhynchos*
Blue-winged Teal	*Anas discors*
Northern Shoveler	*A. Clypeata*
Northern Pintail	*Anas acuta*
Green-winged Teal	*Anas crecca*
Canvasback	*Aythya valisineria*
Redhead	*Aythya americana*
Ring-necked Duck	*Aythya collaris*
Greater and Lesser Scaup	*Aythya marila A. affinis*
Surf Scoter	*Melanitta perspicillata*
White-winged Scoter	*Melanitta fusca*
Black Scoter	*Melanitta nigra*
Long-tailed Duck	*Clangula hyemalis*
Bufflehead	*Bucephala albeola*
Common Goldeneye	*Bucephala clangula*
Hooded Merganser	*Lophodytes cucullatus*
Common Merganser	*Mergus merganser*
Red-Breasted Merganser	*Mergus serrator*
Ruddy Duck	*Oxyura jamaicensis*
Bald Eagle	*Haliaeetus leucocephalus*
Osprey	*Pandion haliaetus*
American Coot	*Fulica americana*
American Oystercatcher	*Heamatopus palliatus*

12.29. Blue crab juvenile VIMS

Table 29. Fall and spring abundance estimates of blue crab 0-group from the VIMS Trawl Survey. Average is estimated from standardized (for mean) values from the two series.

Fall	Spring	Average

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1978		8.1	0.79
1979	0.4	2.7	0.17
1980	7.8	33.3	2.44
1981	6.6	8.4	1.10
1982	3.2	16.6	1.14
1983	6.3	34.3	2.33
1984	2.7	14.7	1.00
1985	3.8	5.5	0.67
1986	1.6	7.9	0.55
1987	2.8	9.5	0.76
1988	2.5	9.6	0.73
1989	9	22.8	2.05
1990	12.8	3.5	1.51
1991	7.8	4.3	1.02
1992	5.5	6.4	0.89
1993	5.8	7.3	0.96
1994	3.6	4.6	0.60
1995	6.7	5.4	0.96
1996	3.7	5.3	0.65
1997	2.7	3.1	0.43
1998	7.2	1.9	0.84
1999	2.4		0.50
2000	2.4		0.50
2001	2.8		0.58

12.30. Blue crab 1+ series

Table 30. Estimates of 1-group and older from the VIMS Trawl Surveys. Average is estimated from standardized (for mean) values from the four series.

Strata	Rivers	Rivers	Rivers	Lower rivers	Lower rivers and bays	
Season	Spring	Summer				
Year\Age	1	1	2+	Ad. fem.	Ad. fem.	Average
1977			2.3	2.3		1.05
1978	4.5	4	2.7	2.6		1.05
1979	1	6.7	5.3	4.5		1.47
1980	10.9	15.5	4.3	3.7		2.25
1981	7.5	8.3	2.8	4.2		1.63
1982	5	10	1.4	1.4		1.06
1983	2.8	8.5	1.5	2.7		1.03

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1984	4.6	9	3.2	2.5		1.32
1985	3.2	3.2	2.4	2.4		0.88
1986	3.5	3.6	3.7	2.5	4.7	1.35
1987	7.4	5.6	3.8	2.2	4.8	1.60
1988	6	7.1	7.4	4.2	7.9	2.42
1989	15	13.8	3.8	1.5	2.6	1.96
1990	4.6	4.4	2.3	1.6	0.8	0.81
1991	2.9	4.9	0.7	0.6	1.3	0.57
1992	2.3	1.9	0.5	0.8	0.8	0.38
1993	1.9	2.6	0.6	1.4	0.4	0.41
1994	2	3.7	0.6	1	1.3	0.51
1995	1.8	3.3	0.6	0.8	0.7	0.41
1996	1.4	3.7	0.7	0.8	0.2	0.36
1997	1.5	2.9	0.8	1.2	0.4	0.40
1998	1.5	3.6	0.6	1.1	0.4	0.40
1999	1.4	2.5	0.9	1.7	0.4	0.44
2000	2.3	3				0.54

12.31. Blue Crab effort, biomass and Z

Table 31. Blue crab effort (relative) and effort (relative) based on CBSAC assessment information (Rugolo *et al.*, 1997). Also, biomasses for juvenile and adult from VIMS surveys (relative).

Year	Effort	CPUE	B, juv. Survey	B, ad. survey
1950	1.00	0.46236		
1951	0.79	0.405534		
1952	0.95	0.441696		
1953	0.88	0.384869		
1954	0.99	0.340958		
1955	1.02	0.260885		
1956	1.23	0.281549		
1957	1.18	0.266051		
1958	1.55	0.229888		
1959	1.78	0.160147		
1960	1.57	0.222139		
1961	1.76	0.263468		
1962	1.97	0.276383		
1963	1.68	0.191143		
1964	1.80	0.263468		

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1965	2.24	0.260885		
1966	2.03	0.271217		
1967	1.98	0.242804		
1968	2.28	0.170479	1.62	0.338404
1969	2.42	0.160147	0.37	2.01991
1970	2.02	0.170479	3.23	1.724863
1971	2.00	0.227305	2.26	3.444509
1972	1.88	0.21439	0.65	1.208093
1973	1.81	0.183394	0.69	0.717653
1974	1.95	0.211807	0.19	1.041664
1975	2.23	0.175645	0.33	0.813026
1976	2.39	0.123985	0.51	0.768989
1977	2.79	0.147232	1.20	0.970036
1978	3.30	0.113653	0.93	0.980441
1979	2.95	0.131734	0.48	1.201086
1980	4.50	0.118819	1.95	1.335122
1981	4.02	0.144649	1.87	3.54139
1982	3.44	0.147232	1.10	1.597249
1983	3.25	0.183394	1.92	2.738698
1984	3.03	0.178228	1.35	2.211042
1985	3.31	0.18856	1.34	2.731345
1986	3.15	0.149815	1.13	1.977338
1987	2.89	0.1369	1.01	0.987511
1988	3.24	0.160147	0.85	1.050354
1989	2.66	0.157564	3.00	2.295053
1990	3.07	0.209224	3.45	2.268291
1991	2.81	0.183394	1.06	2.439308
1992	3.68	0.118819	2.59	1.732251
1993	3.00	0.185977	1.77	1.676205
1994	3.72	0.16273	1.13	1.433946
1995		0.121402	2.22	0.978252
1996			1.98	1.388185
1997			0.92	1.158834
1998			1.55	0.692759
1999			0.91	0.910506
2000			0.85	0.762571
2001				
2002				

12.32. Blue crab catches

Table 32. Catches, abundance estimates and fishing mortalities (F) for blue crab in the Chesapeake Bay. Based on CBSAC (2003). In addition to the commercial catches we

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added 25% as estimate for recreational catches. The F-series is not used for driving Ecosim.

Year	Commercial catch (lbs)	Commercial catch (t)	Catch ($t \cdot km^{-2} \cdot year^{-1}$)	1+ abundance	0 abundance	F ($year^{-1}$)
1950	76080000	34519	3.45			
1951	67620000	30681	3.07			
1952	60960000	27659	2.77			
1953	61140000	27740	2.77			
1954	51420000	23330	2.33			
1955	43500000	19737	1.97			
1956	48180000	21860	2.19			0.97
1957	54840000	24882	2.49			1.15
1958	46200000	20962	2.10			1.12
1959	41880000	19002	1.90			1.10
1960	66000000	29946	2.99			1.08
1961	69780000	31661	3.17			1.12
1962	81300000	36887	3.69			1.13
1963	61680000	27985	2.80			1.11
1964	72660000	32967	3.30			1.09
1965	79500000	36071	3.61			1.08
1966	102000000	46198	4.62			1.09
1967	83460000	37868	3.79			1.11
1968	56280000	25535	2.55	-1.15	0.15	0.76
1969	60960000	27659	2.77	0.58	-1.14	0.85
1970	67800000	30762	3.08	0.25	1.79	0.73
1971	75360000	34192	3.42	2.03	0.77	0.90
1972	71760000	32559	3.26	-0.24	-0.89	0.82
1973	55920000	25372	2.54	-0.77	-0.80	0.81
1974	62940000	28557	2.86	-0.44	-1.34	0.79
1975	57180000	25944	2.59	-0.67	-1.20	0.69
1976	46200000	20962	2.10	-0.71	-1.01	0.71
1977	57720000	26189	2.62	0.00	-0.30	0.68
1978	52680000	23902	2.39	-0.60	-0.58	0.74
1979	71760000	32559	3.26	-0.50	-1.05	0.75
1980	60240000	27332	2.73	-0.38	0.45	0.67
1981	102000000	46198	4.62	2.12	0.39	0.85
1982	87780000	39828	3.98	0.05	-0.40	0.73
1983	96780000	43911	4.39	0.99	0.44	0.75
1984	96600000	43829	4.38	1.39	-0.15	0.83
1985	97500000	44238	4.42	0.97	-0.14	0.94
1986	83820000	38031	3.80	0.22	-0.36	0.78
1987	74640000	33866	3.39	-0.46	-0.47	0.65
1988	78240000	35499	3.55	-0.31	-0.66	0.73
1989	86880000	39419	3.94	0.52	1.58	0.79
1990	1.01E+08	45626	4.56	0.70	2.06	0.76
1991	95700000	43421	4.34	0.67	-0.44	0.76
1992	57720000	26189	2.62	0.45	1.18	0.83

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1993	1.14E+08	51588	5.16	0.34	0.32	0.86
1994	84180000	38194	3.82	-0.16	-0.32	0.96
1995	76620000	34764	3.48	-0.51	0.80	0.85
1996	75900000	34437	3.44	0.30	0.55	0.96
1997	86700000	39338	3.93	-0.14	-0.57	0.90
1998	61860000	28067	2.81	-0.83	0.11	0.79
1999	67440000	30599	3.06	-0.46	-0.58	0.85
2000	51060000	23167	2.32	-0.80	-0.60	0.86
2001	52320000	23739	2.37	-0.86	-0.50	0.81
2002	54300000	24637	2.46	-0.52	-0.50	0.87
2003	46380000	21044	2.10	-0.56	-0.11	

12.33. Diet compositions for commercial invertebrates

Table 33. Diet compositions for commercial invertebrates. Diet compositions are expressed as proportions and are on a volume or weight basis. For sources see text.

	Prey \ Predator	Blue crab YOY	Blue crab adult	Oyster YOY	Oyster 1+	soft clam	Hard clam
30	Blue crab YOY		0.25				
32	Oyster YOY	0.039	0.05				
34	soft clam	0.021	0.07				
35	Hard clam	0.021	0.16				
38	Microzooplankton				0.09	0.09	
40	other suspension feeders		0.05				
41	Other in/epi fauna	0.451	0.25				
42	benthic algae	0.105	0.03				0.5
43	SAV		0.03				
44	Phytoplankton			1	0.9	0.9	0.25
45	Detritus	0.362	0.11		0.01	0.01	0.25

12.34. Oyster effort and abundance

Table 34. Oyster effort (relative) and abundance estimates in form of a relative time series, and a relative catch per unit effort for Maryland (CPUE, Maryland DNR) series. The CPUE estimates were used for fitting of the stock reduction analysis, from which the estimated biomass, recruitment and fishing mortalities (F) are presented.

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Year	Effort	Relative abundance	CPUE (bushels / person / day)	Biomass ($t \cdot km^{-2}$)	Recruitment ($t \cdot km^{-2} \cdot year^{-1}$)	F ($year^{-1}$)
1950	1.00			20.41	7.15	0.07
1951	1.00			19.56	6.88	0.07
1952	1.00			18.76	6.64	0.08
1953	1.00			17.85	6.36	0.09
1954	1.00			16.92	6.06	0.11
1955	1.00			15.90	5.74	0.11
1956	1.00			14.98	5.44	0.11
1957	1.00			14.14	5.16	0.11
1958	1.00			13.38	4.91	0.13
1959	1.00			12.57	4.64	0.12
1960	1.00			11.88	4.41	0.10
1961	1.00			11.37	4.23	0.11
1962	1.00			10.85	4.05	0.08
1963	0.96			10.54	3.95	0.08
1964	0.92			10.28	3.86	0.10
1965	0.88			9.92	3.73	0.10
1966	0.84			9.58	3.61	0.10
1967	0.80			9.24	3.49	0.13
1968	0.76			8.78	3.33	0.12
1969	0.72			8.41	3.20	0.12
1970	0.68			8.05	3.07	0.14
1971	0.64			7.62	2.91	0.15
1972	0.60			7.16	2.75	0.15
1973	0.56			6.74	2.59	0.17
1974	0.57			6.29	2.43	0.18
1975	0.57	1.00	16.1	5.84	2.26	0.18
1976	0.57	0.94	15.5	5.44	2.11	0.17
1977	0.57	0.88	12.1	5.08	1.98	0.16
1978	0.54	0.97	14.7	4.79	1.87	0.21
1979	0.56	0.94	14.7	4.39	1.72	0.22
1980	0.64	0.84	13.7	4.00	1.57	0.26
1981	0.64	0.66	14.3	3.57	1.41	0.27
1982	0.57	0.53	13.1	3.17	1.25	0.25
1983	0.48	0.45	9.4	2.86	1.13	0.18
1984	0.53	0.42	8.1	2.68	1.06	0.21
1985	0.58	0.37	7.8	2.47	0.98	0.24
1986	0.53	0.32	9.8	2.24	0.89	0.28
1987	0.25	0.25	6.7	1.99	0.79	0.20
1988	0.26	0.20	5.2	1.86	0.74	0.13
1989	0.29	0.16	5.5	1.80	0.72	0.11
1990	0.29	0.12	5.2	1.77	0.71	0.12
1991	0.22	0.12	5.2	1.73	0.69	0.09
1992	0.10	0.07	5.3	1.72	0.69	0.06
1993	0.05	0.15	4.6	1.74	0.70	0.01
1994	0.10	0.08	6.2	1.81	0.72	0.03
1995	0.10	0.09	5.7	1.87	0.74	0.04
1996	0.11	0.09	6.9	1.91	0.76	0.02

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1997	0.16	0.12	5.8	1.97	0.79	0.04
1998	0.26	0.13	6.5	2.02	0.80	0.06
1999	0.17	0.16	5.8	2.04	0.81	0.06
2000	0.15	0.16	7.9	2.06	0.82	0.06
2001				2.08	0.83	0.03
2002				2.14	0.85	0.01

12.35. Hurricanes and flooding

Table 35. Occurrence of hurricanes in the Maryland/Virginia region, and assumed impact on the relative P/B for soft and hard clam. Data sources: http://www.vdem.state.va.us/library/vahurr/va-hurr.htm and http://www.nhc.noaa.gov/HAW2/english/history.shtml#iris.

Year	Date	Name	Hurricane category	VA/MD flooding	Guessed P/B (relative)
1952	31-Aug	Able	Weak	minor	0.7
1953	14-Aug	Barbara	Weak		0.9
1954	15-Oct	Hazel	4		0.9
1955	12-Aug	Connie	Weak	minor	0.7
1955	17-Aug	Diane	1	minor	-
1955	19-Sep	Ione	Weak		-
1956	27-Sep	Flossy	Weak		0.9
1959	10-Jul	Cindy	Weak		0.9
1959	30-Sep	Gracie	3		0.9
1960	12-Sep	Donna	4	major	0.1
1964	01-Sep	Cleo	weak	heavy rains	0.7
1969	20-Aug	Camille	5	historic record	0.1
1971	27-Aug	Doria	TS	minor	0.7
1972	21-Jun	Agnes	1	major	0.1
1979	05-Sep	David	2		0.9
1985	25-Jul	Bob	2		-
1985	27-Sep	Gloria	3	moderate	0.4
1986	17-Aug	Charley	weak	minor	0.7
1996	12-Jul	Bertha	weak		-
1996	05-Sep	Fran	3	major	0.1
1997	24-Jul	Danny		minor	0.7
1998	27-Aug	Bonnie	2	moderate	0.4
1999	04-Sep	Dennis		minor	-
1999	15-Sep	Floyd	2	major	0.1
2001	14-Jun	Allison	TS		0.9
2003	18-Sep	Isabel	3	major	0.1

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12.36. Related P/B values for soft and hard clam

Table 36. Guessed relative-P/B for soft and hard clam assuming that the impacts of hurricanes are carried over to subsequent years, although with less severity (last column).

Year	P/B (relative, from Table 36Table 35)	P/B (relative), used to force simulations
1950	1	1
1951	1	1
1952	0.7	0.7
1953	0.9	0.8
1954	0.9	0.9
1955	0.7	0.7
1956	0.9	0.8
1957	1	0.9
1958	1	1
1959	0.9	0.9
1960	0.1	0.1
1961	1	0.2
1962	1	0.3
1963	1	0.4
1964	0.7	0.5
1965	1	0.6
1966	1	0.7
1967	1	0.8
1968	1	0.9
1969	0.1	0.1
1970	1	0.2
1971	0.7	0.3
1972	0.1	0.1
1973	1	0.2
1974	1	0.3
1975	1	0.4
1976	1	0.5
1977	1	0.6
1978	1	0.7
1979	0.9	0.8
1980	1	0.9
1981	1	1
1982	1	1
1983	1	1
1984	1	1
1985	0.4	0.4

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1986	0.7	0.5
1987	1	0.6
1988	1	0.7
1989	1	0.8
1990	1	0.9
1991	1	1
1992	1	1
1993	1	1
1994	1	1
1995	1	1
1996	0.1	0.1
1997	0.7	0.2
1998	1	0.3
1999	0.1	0.1
2000	1	0.2
2001	0.9	0.3
2002	1	0.4
2003	0.1	0.1
2004	1	0.2

12.37. Zooplankton

Table 37. Estimate of relative abundance for mesozooplankton and microzooplankton in the Chesapeake Bay, 1985-1999.

year	Mesozooplankton	Microzooplankton
1985	8.5	23
1986	6.1	22
1987	3.1	26
1988	1.4	27
1989	4.8	34
1990	5.7	23
1991	4.1	26
1992	2.8	27
1993	3.8	56
1994	2.3	61
1995	2.3	60
1996	3.3	43
1997	2.5	46
1998	2.7	31
1999	2.0	37

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12.38. Diet compositions for other invertebrates

Table 38. Diet compositions for other invertebrates expressed as proportions on a weight or volume basis. The diet compositions are based on general knowledge about the groups. Numbers in the first column refer to EwE groups numbers.

	Prey \ Predator	ctenophores	sea nettles	Micro-zooplankton	Meso-zooplankton	other suspension feeders	Other in/epi fauna
23	reef assoc. fish		0.001				
25	Littoral forage fish		0.053				
36	Ctenophores		0.525				
38	Microzooplankton	0.334			0.72		0.08
39	Mesozooplankton	0.666	0.421				
41	Other in/epi fauna						0.02
42	benthic algae					0.25	0.3
44	Phytoplankton			1	0.28	0.5	0.4
45	Detritus					0.25	0.2

12.39. Phytoplankton chlorophyll

Table 39. Estimate of relative chlorophyll content for Chesapeake Bay, 1950-1994 (Harding and Perry, 1997). The series is used for comparison with Ecosim simulation results, not for driving the model.

Year	Chlorophyll
1950	4.2
1951	3.8
1952	1.9
1964	4.9
1965	4.3
1966	4.6
1967	4.3
1968	4.7
1969	2.8
1970	3.5
1971	3.7
1972	4.9
1973	5.5
1974	4.1

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1975	5.0
1976	4.4
1977	4.6
1978	5.0
1979	4.1
1980	4.7
1981	3.6
1982	
1983	3.0
1984	4.7
1985	4.8
1986	4.8
1987	5.0
1988	4.8
1989	4.9
1990	4.9
1991	4.6
1992	4.4
1993	4.7
1994	4.7

12.40. Confidence intervals

Table 40. Estimate of confidence intervals for basic input parameters of the 1950-model of the Chesapeake Bay. The confidence intervals are derived from the model pedigree, see the EwE User's Guide for information (Christensen *et al.*, 2004).

	Group	B	P/B	Q/B	Diet	Catch
1	Striped bass YOY	50	50	50	10	---
2	Striped bass resident	50	10	50	10	50
3	Striped bass migratory	50	10	50	10	50
4	Bluefish YOY	50	50	50	10	---
5	Bluefish adult	50	50	50	10	50
6	Weakfish YOY	50	50	50	10	---
7	Weakfish Adult	50	50	50	10	50
8	Atl. croaker	50	10	50	60	50
9	black drum	80	10	50	30	50
10	Summer flounder	80	40	50	30	50
11	Menhaden YOY	50	50	50	50	50
12	Menhaden adult	50	50	50	50	50
13	Alewife and herring	80	20	50	50	50
14	American eel	80	20	50	60	50
15	Catfish	80	20	50	60	50
16	White perch YOY	50	50	50	10	---

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17	White perch adult	50	50	50	60	50
18	Spot	80	10	50	30	50
19	American shad	50	30	50	10	50
20	bay anchovy	50	30	50	50	---
21	Other flatfish	80	50	50	60	---
22	gizzard shad	80	50	50	60	---
23	reef assoc. fish	80	10	50	60	---
24	non reef assoc. fish	80	70	50	60	---
25	Littoral forage fish	80	70	50	10	---
26	sandbar shark	50	70	50	60	50
27	other elasmobranchs	50	70	50	30	---
28	Piscivorous birds	50	40	50	60	---
29	Non-piscivorous seabirds	50	40	50	60	---
30	Blue crab YOY	50	70	50	10	---
31	Blue crab adult	50	10	50	30	50
32	Oyster YOY	50	70	50	60	---
33	Oyster 1+	50	50	50	60	50
34	soft clam	80	50	50	60	50
35	Hard clam	50	50	50	30	50
36	Ctenophores	80	40	50	60	---
37	sea nettles	80	40	50	60	---
38	Microzooplankton	80	70	50	60	---
39	Mesozooplankton	50	40	50	60	---
40	other suspension feeders	80	50	50	60	---
41	Other in/epi fauna	80	50	50	60	---
42	benthic algae	80	70	---	---	---
43	SAV	80	20	---	---	---
44	Phytoplankton	80	40	---	---	---

12.41. Prices

Table 41. Year 2000 prices ($US) for commercial catches of exploited groups in the Chesapeake Bay. For group 13, alewife/herring we used the price for alewife as these dominated the landings (98.6%). For group 15, catfish we used the average price for the two most common species, (blue and channel catfish). Source: www.seaaroundus.org.

Group	Name	$/kg
2, 3	Striped bass	3.91
5	Bluefish	0.77
7	Weakfish, grey	1.51
8	Atlantic croaker	0.83
9	Black drum	1.56
10	Summer flounder	3.94

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12	Atlantic Menhaden	0.14
13	Alewife	0.44
13	Atlantic herring	0.14
14	American eel	1.80
15	Catfish, blue	1.06
15	Catfish, channel	1.13
15	Catfish, flathead	1.03
17	White perch	1.14
18	Spot	1.14
19	American shad	0.63
26	Sandbar shark	0.71
31	Blue crab	1.79
33	Oyster, American cupped	0.74
34	Soft clam	5.48
35	Hard clam (quahog)	9.70

12.42. Vulnerabilities

Table 42. Vulnerability settings for groups in the 1950-ecosystem model. Only groups for which the vulnerabilities were changed from the default value of 2 are displayed.

	Group	Vulnerability
2	Striped bass resident	5
3	Striped bass migratory	10
4	Bluefish YOY	10
5	Bluefish adult	10
6	Weakfish YOY	1
7	Weakfish Adult	1.2
8	Atl. croaker	1
9	black drum	1.5
10	Summer flounder	1
11	Menhaden juv.	1.2
13	Alewife and herring	1
14	American eel	1
18	Spot	6
20	bay anchovy	1.13
25	Littoral forage fish	1
28	Piscivorous birds	100
30	Blue crab YOY	1.1
31	Blue crab adult	1.1
33	Oyster 1+	3
35	Hard clam	1.7
36	ctenophores	100
38	Microzooplankton	1

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39	Mesozooplankton	1
41	Other in/epi fauna	1

12.43. Bay anchovy simulation

Table 43. Estimated change in biomass of ecosystem groups resulting from applying a strong fishing pressure on bay anchovy. Groups for which the predicted change was less than ±5% are omitted.

Group	**Change (%)**
Other flatfish	21
Spot	17
Sea nettles	12
Hard clam	11
Ctenophores	11
Striped bass resident	10
Catfish	9
Striped bass migratory	7
Atl. croaker	-7
Sandbar shark	-12
Summer flounder	-13
Other elasmobranchs	-13
Reef assoc. fish	-15
Bluefish adult	-21
Weakfish Adult	-34
White perch adult	-39
Piscivorous birds	-47
Bluefish YOY	-51
Weakfish YOY	-64
Bay anchovy	-84

12.44. Oyster: no fishing

Table 44. Predicted effect on group biomasses if fishing for oyster had been stopped since 1950. The biomass ratios are expressed as current biomass (assuming no oyster fishing) /

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current biomass (with historic oyster fishing). Only groups for which the absolute difference exceeds 5% are included in the table.

Group	Biomass ratio
Oyster 1+	4.28
Oyster YOY	3.14
Weakfish Adult	0.95
Summer flounder	0.94
Phytoplankton	0.94
other elasmobranchs	0.94
Striped bass YOY	0.93
Non-piscivorous seabirds	0.93
Menhaden adult	0.92
Piscivorous birds	0.92
Menhaden YOY	0.91
other suspension feeders	0.90
Striped bass migratory	0.89
Striped bass resident	0.88
black drum	0.74
ctenophores	0.73
sea nettles	0.69
Catfish	0.67
Bluefish adult	0.67
soft clam	0.63
Bluefish YOY	0.60
Hard clam	0.41

12.45. Buchanan PP volumes

Table 45. Segment volumes (from D. Jasinski) and mean depths (from M. Olson). F, Tidal Fresh (0-0.5 ppt); O, Oligohaline (0.5-5 ppt); M, Mesohaline (5-18 ppt); P, Polyhaline (>18 ppt).

Sal-zone	Representative biomonitoring station in segment	Segment name	Mean station depth (m)	Mean segment depth (m)	Segment volume (10^6 m^3)	Salzone subtotal (10^6 m^3)	Volume subtotal of segments w/o biomonitoring station (10^6 m^3)	Volume subtotal (10^6 m^3)
F	TF1.5	PAXTF	10.3	11.1	11.025			
F	CB1.1, CB2.1	CB1TF	5.9	7.4	360.000			
F	TF4.2	PMKTF	7.0	7.0	28.630			
F	TF2.3	POTTF	12.5	12.9	484.750			
F	TF5.5	JMSTF	8.8	9.8	286.188	1,170.593	192.905	1,363.498
O	ET5.1	CHOOH	5.9	10.5	45.125			

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O	TF1.7	PAXOH	2.8	5.0	27.180			
O	TF3.3	RPPOH	6.3	7.0	53.580			
O	RET5.2	JMSOH	8.0	11.5	431.500			
O	CB2.2	CB2OH	12.0	13.8	1,237.000			
O	RET2.2	POTOH	9.8	9.4	852.250	2,646.635	629.950	3,276.585
M	SBE2, SB5	SBEMH	13.0, 8.1	9.0	27.730			
M	ET5.2	CHOMH	11.4	13.5	266.750			
M	RET4.3	YRKMH	5.2	7.0	275.500			
M	WT5.1	PATMH	14.4	16.5	451.500			
M	LE5.5	JMSMH	17.0	7.3	977.000			
M	LE1.1	PAXMH	11.9	16.6	561.000			
M	CB3.3C	CB3MH	23.9	14.0	2,391.000			
M	LE3.6, RET3.1	RPPMH	9.1, 5.4	9.0	1,482.250			
M	LE2.2	POTMH	11.2	16.5	5,792.000			
M	CB4.3C	CB4MH	26.9	24.6	9,237.000			
M	CB5.2	CB5MH	30.1	18.3	15,416.000	36,877.730	8,225.525	45,106.255
P	WE4.2	MOBPH	13.6	7.3	1,342.500			
P	CB6.1, CB6.4	CB6PH	12.8, 10.0	11.0	6,503.000			
P	CB7.3E	CB7PH	17.1	16.0	13,523.000			
P	CB7.4	CB8PH	13.3	12.7	3,172.000	24,540.500	912.980	25,453.480
All						65,235.458	9,964.360	75,199.818

12.46. PP segments

Table 46. Adjustment factors used to estimate masses for whole Bay from masses for CBP segments with representative biomonitoring stations. Adjustment factors are specific to each salinity zone, and are calculated by dividing [total volume] by [volume with representative biomonitoring stations].

Salinity zone	Total volume of all segments in salinity zone ($10^6 m^3$)	Total volume with rep. biomon. stations ($10^6 m^3$)	Total volume w/o rep. biomon. stations ($10^6 m^3$)	Adjustment factor for nano, micro, phyto biomass, POC chlorophyll, pheophytin	Volume of VA segments with rep. biomon. stations ($10^6 m^3$)	Adjustment factor for pico-phytoplankton biomass
Tidal fresh	1,363.498	1,170.593	192.905	1.165	314.818	4.331
Oligohaline	3,276.585	2,646.635	629.950	1.238	485.080	6.755
Mesohaline	45,106.255	36,877.730	8,228.525	1.223	2,762.480	16.328
Polyhaline	25,453.480	24,540.500	912.980	1.037	24,540.500	1.037
Grand Total	75,199.818	65,265.458	9,964.360		28,102.878	

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12.47. *Phytoplankton biomass*

Table 47. Monthly estimates of total mass (kg) for nano- micro- phytoplankton biomass (as carbon), chlorophyll, pheophytin, particulate organic carbon, and pico-phytoplankton biomass (as carbon) in Chesapeake Bay, by salinity zone, and adjusted to reflect masses in all CBP segments.

Salinity zone	Month	Nano-micro-phytoplankton biomass (kgC)	Chlorophyll (kgC)	Pheophytin (kgC)	Particulate organic carbon (kgC)	Pico-phytoplankton biomass (kgC)	Total phytoplankton biomass (kgC)
TF	1	170,819	3,408	3,512	1,795,395	5,802	176,621
TF	2	268,440	4,534	2,710	1,076,204	3,966	272,406
TF	3	309,099	6,617	2,979	1,221,436	5,397	314,496
TF	4	528,048	11,100	5,715	1,343,853	14,722	542,771
TF	5	764,377	17,211	9,729	1,822,617	62,019	826,396
TF	6	882,321	21,451	9,161	1,664,270	365,935	1,248,256
TF	7	1,303,405	27,485	11,178	3,086,113	345,090	1,648,495
TF	8	1,402,838	28,380	13,134	2,011,839	495,816	1,898,654
TF	9	806,560	20,896	9,730	2,062,872	262,868	1,069,428
TF	10	975,243	19,401	11,354	1,601,482	128,178	1,103,421
TF	11	721,858	11,203	8,179	1,472,989	26,450	748,308
TF	12	296,842	5,277	4,677	1,461,755	13,575	310,417
OH	1	509,986	9,800	8,833	3,640,032	37,127	547,113
OH	2	773,715	14,816	6,551	3,870,334	18,329	792,044
OH	3	843,654	27,885	10,608	5,657,401	29,154	872,808
OH	4	951,748	21,308	16,578	4,397,120	43,643	995,391
OH	5	739,798	20,187	15,797	4,708,773	146,674	886,472
OH	6	634,494	15,504	11,400	3,916,773	850,964	1,485,458
OH	7	922,315	21,244	11,674	3,385,662	738,056	1,660,371
OH	8	897,085	23,797	11,938	3,637,102	1,066,538	1,963,623
OH	9	787,682	18,302	10,927	3,022,171	872,548	1,660,230
OH	10	553,988	16,513	9,855	2,848,737	575,998	1,129,986
OH	11	493,474	12,574	7,639	3,206,912	144,471	637,946
OH	12	407,791	10,827	8,796	3,168,559	74,957	482,748
MH	1	14,763,173	342,998	79,509	35,241,506	41,258	14,804,431
MH	2	29,988,522	536,496	91,627	54,048,193	29,096	30,017,618
MH	3	26,982,454	523,141	71,976	52,518,542	26,450	27,008,904
MH	4	30,413,545	603,992	88,141	58,406,828	43,023	30,456,569
MH	5	17,095,406	378,718	77,898	47,962,985	201,415	17,296,820
MH	6	10,868,591	261,321	69,296	39,083,262	1,624,934	12,493,525
MH	7	9,253,575	247,696	74,080	37,774,147	2,262,195	11,515,771
MH	8	8,589,254	239,690	72,545	36,381,569	3,047,718	11,636,972
MH	9	10,606,531	240,674	73,514	32,516,953	1,435,963	12,042,494
MH	10	10,336,535	237,443	90,770	28,932,131	632,187	10,968,722
MH	11	8,572,135	206,907	88,983	26,390,593	190,805	8,762,939
MH	12	10,522,855	221,184	87,380	26,659,903	92,305	10,615,160
PH	1	9,558,556	190,874	35,790	17,099,814	358,002	9,916,558

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PH	2	12,986,621	185,788	37,297	20,759,465	188,079	13,174,700
PH	3	13,816,607	182,847	30,589	21,192,801	167,248	13,983,855
PH	4	17,519,683	224,313	25,134	25,412,790	285,842	17,805,525
PH	5	11,433,229	158,644	32,043	20,840,193	907,294	12,340,523
PH	6	6,031,000	120,779	36,962	20,271,481	7,332,497	13,363,497
PH	7	5,059,760	128,544	31,311	22,040,800	10,433,259	15,493,019
PH	8	9,861,708	158,541	44,771	19,587,782	9,539,313	19,401,022
PH	9	7,791,910	118,025	57,439	17,314,969	5,659,048	13,450,958
PH	10	11,786,129	128,778	41,485	13,848,431	2,628,770	14,414,899
PH	11	6,967,193	119,451	34,715	16,346,305	935,923	7,903,116
PH	12	6,203,911	109,221	35,522	18,070,868	591,522	6,795,433
All	1	25,002,534	547,079	127,643	57,776,747	442,189	25,444,723
All	2	44,017,298	741,633	138,186	79,754,197	239,470	44,256,768
All	3	41,951,814	740,490	116,152	80,590,180	228,249	42,180,063
All	4	49,413,025	860,713	135,568	89,560,592	387,230	49,800,255
All	5	30,032,809	574,760	135,466	75,334,568	1,317,402	31,350,212
All	6	18,416,405	419,055	126,819	64,935,786	10,174,331	28,590,736
All	7	16,539,055	424,969	128,243	66,286,722	13,778,601	30,317,655
All	8	20,750,886	450,408	142,388	61,618,292	14,149,385	34,900,271
All	9	19,992,683	397,897	151,610	54,916,965	8,230,428	28,223,111
All	10	23,651,895	402,136	153,464	47,230,781	3,965,133	27,617,028
All	11	16,754,660	350,135	139,516	47,416,799	1,297,648	18,052,308
All	12	17,431,398	346,508	136,375	49,361,086	772,359	18,203,757
Annual		26,996,205	521,315	135,953	64,565,226	4,581,869	31,578,074

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12.48. River stations for nitrogen data

Table 48. Chesapeake Bay river station descriptions for total nitrogen data

STATION	WATER_BODY	DESCRIPTION	LAT	LONG
CB1.1	SUSQUEHANNA RIVER	MOUTH OF SUSQUEHANNA RIVER; HEAD OF BAY; MID-CHANNEL	39.545113	-76.08134
ET5.2	CHOPTANK RIVER	LOWER CHOPTANK RIVER NEAR ROUTE 50 BRIDGE AT CAMBRIDGE; CHARACTERIZES	38.58012	-76.058

		LOWER ESTUARINE		
ET6.	NANTICOKE RIVER	LOWER NANTICOKE RIVER; MID-CHANNEL NEAR BUOY FIG-11; CHARACTERIZES LOWER ESTUARINE	38.333454	-75.88299
LE1.4	PATUXENT RIVER	MID-CHANNEL BETWEEN DRUM POINT AND FISHING POINT; CHARACTERIZES LOWER ESTUARINE	38.31207	-76.42134
LE2.3	POTOMAC RIVER	MOUTH OF POTOMAC RIVER; BOUNDARY BETWEEN CB5 AND LE2; RIVER CHANNEL	38.021515	-76.347725
LE3.6	RAPPAHANNOCK RIVER	MOUTH OF THE RAPPAHANNOCK RIVER	37.596798	-76.28467
LE5.5	JAMES RIVER	MOUTH OF THE JAMES RIVER	36.999035	-76.31328
WE4.2	YORK RIVER	MOUTH OF THE YORK RIVER; MID-CHANNEL	37.24181	-76.38634
WT5.1	PATAPSCO RIVER	PATAPSCO RIVER; EAST OF HAWKINS POINT AT BUOY 5M; CHARACTERIZES LOWER ESTUARINE	39.208443	-76.52469

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12.49. Chesapeake Bay stations for nitrogen data

Table 49. Station descriptions for Chesapeake Bay total nitrogen time series data.

STATION	CBP_BASIN	DESCRIPTION	LAT	LONG
CB2.1	MD EASTERN SHORE	SOUTHWEST OF TURKEY POINT; UPPER LIMIT OF TRANSITION ZONE; MID-CHANNEL	39.440113	-76.024666
CB2.2	MD EASTERN SHORE	WEST OF STILL POND NEAR BUOY R-34; MIDDLE OF TRANSITION ZONE; MID-CHANNEL	39.346775	-76.174675
CB3.1	MD EASTERN SHORE	SOUTHEAST OF GUNPOWDER NECK BETWEEN BUOY 24A AND 24B; LOWER LIMIT OF TRANSITION ZONE; MID-CHANNEL	39.248444	-76.23801
CB3.2	MD EASTERN SHORE	NORTHWEST OF SWAN POINT NEAR BUOY R-10; LOWER ESTUARINE REACH; MID-CHANNEL	39.163445	-76.30634
CB3.3C	MD WESTERN SHORE	NORTH OF BAY BRIDGE; CHARACTERIZES MID-CHANNEL	38.995113	-76.35968
CB3.3E	MD EASTERN SHORE	NORTHEAST OF BAY BRIDGE; CHARACTERIZES EASTERN SHORE	39.001778	-76.346344
CB3.3W	MD WESTERN SHORE	NORTHWEST OF BAY BRIDGE; CHARACTERIZES WESTERN SHORE	39.003445	-76.388016
CB4.1C	MD EASTERN SHORE	SOUTHWEST OF KENT POINT; CHARACTERIZES MID-CHANNEL	38.825115	-76.39967
CB4.1E	MD EASTERN	SOUTH OF KENT POINT; BOUNDARY BETWEEN	38.816505	-76.37106

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	SHORE	CB4 AND EE1; RIVER CHANNEL		
CB4.1W	MD WESTERN SHORE	SOUTHEAST OF HORSESHOE POINT; CHARACTERIZES WESTERN SHORE	38.81345	-76.46273
CB4.2C	MD EASTERN SHORE	SOUTHWEST OF TILGHMAN ISLAND NEAR BUOY CR; CHARACTERIZES MID-CHANNEL	38.64484	-76.41773
CB4.2E	MD EASTERN SHORE	SOUTHWEST OF TILGHMAN ISLAND; CHARACTERIZES EASTERN SHORE	38.64484	-76.39995
CB4.2W	MD WESTERN SHORE	NORTHWEST OF PLUM POINT; CHARACTERIZES WESTERN SHORE	38.64345	-76.50134
CB4.3C	MD EASTERN SHORE	EAST OF DARES BEACH NEAR BUOY R-64; CHARACTERIZES MID-CHANNEL	38.55651	-76.43467
CB4.3E	MD EASTERN SHORE	MOUTH OF CHOPTANK RIVER; BOUNDARY BETWEEN CB4 AND EE2	38.55651	-76.38967
CB4.3W	MD WESTERN SHORE	EAST OF DARES BEACH; CHARACTERIZES WESTERN SHORE	38.55651	-76.49301
CB4.4	MD EASTERN SHORE	NORTHEAST OF COVE POINT; MID-CHANNEL	38.413177	-76.343
CB5.1	MD EASTERN SHORE	EAST OF CEDAR POINT AND PR BUOY; MID-CHANNEL	38.318455	-76.293
CB5.1W	PATUXENT RIVER	MID-CHANNEL BETWEEN CEDAR POINT AND COVE POINT; CHARACTERIZES LOWER	38.325123	-76.3755

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		ESTUARINE		
CB5.2	MD EASTERN SHORE	EAST OF POINT NO POINT; MID-CHANNEL	38.13679	-76.228
CB5.3	VA EASTERN SHORE	NORTHEAST OF SMITH POINT AT VIRGINIA STATE LINE; MID-CHANNEL; OVERLAP STATION WITH VIRGINIA	37.911793	-76.168
CB5.4	VA EASTERN SHORE	CENTRAL CHESAPEAKE BAY (DEEP MAIN CHANNEL)	37.80013	-76.17466
CB5.4W	RAPPAHANNOCK RIVER	CENTRAL CHESAPEAKE BAY AT THE MOUTH OF THE GREAT WICOMICO RIVER	37.813465	-76.29467
CB5.5	RAPPAHANNOCK RIVER	CENTRAL CHESAPEAKE BAY (MAIN CHANNEL)	37.6918	-76.18967
CB6.1	RAPPAHANNOCK RIVER	LOWER WEST CENTRAL CHESAPEAKE BAY (MAIN CHANNEL OFF LOWER END OF THE RAPPAHANNOCK RIVER)	37.588467	-76.16216
CB6.2	RAPPAHANNOCK RIVER	LOWER WEST CENTRAL CHESAPEAKE BAY	37.4868	-76.15633
CB6.3	RAPPAHANNOCK RIVER	LOWER WEST CENTRAL CHESAPEAKE BAY (WOLFTRAP)	37.411526	-76.15966
CB6.4	YORK RIVER	CENTRAL CHESAPEAKE BAY OFFSHORE FROM MOUTH OF YORK RIVER	37.236526	-76.20799

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CB7.1	VA EASTERN SHORE	LOWER EAST CENTRAL CHESAPEAKE BAY (EASTERN SHORE CHANNEL)	37.683464	-75.98966
CB7.1N	VA EASTERN SHORE	LOWER EAST CENTRAL CHESAPEAKE BAY (TANGIER SOUND CHANNEL)	37.775127	-75.97466
CB7.1S	VA EASTERN SHORE	LOWER EAST CENTRAL CHESAPEAKE BAY (EASTERN SHORE CHANNEL)	37.58124	-76.05799
CB7.2	VA EASTERN SHORE	LOWER EAST CENTRAL CHESAPEAKE BAY (EASTERN SHORE CHANNEL)	37.411526	-76.07966
CB7.2E	VA EASTERN SHORE	LOWER EAST CENTRAL CHESAPEAKE BAY (EASTERN SHORE; SIDE CHANNEL)	37.411526	-76.02466
CB7.3	YORK RIVER	MAINSTEM YORK SPIT CHANNEL	37.11681	-76.12521
CB7.3E	VA EASTERN SHORE	LOWER EASTERN SHORE CHANNEL AREA	37.228752	-76.053825
CB7.4	JAMES RIVER	BALTIMORE CHANNEL AT THE BAY BRIDGE/TUNNEL	36.9957	-76.020485
CB7.4N	VA EASTERN SHORE	NORTH CHANNEL AT THE BAY BRIDGE/TUNNEL	37.062366	-75.999374
CB8.1	JAMES RIVER	BETWEEN JAMES RIVER MOUTH AND THIMBLE SHOALS CHANNEL	36.995422	-76.16772
CB8.1E	JAMES RIVER	THIMBLE SHOALS CHANNEL AT BAY BRIDGE/TUNNEL	36.94737	-76.034935

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12.50. River gage station descriptions

Table 50. Descriptions of river gage stations for which flow data was recorded. Virginia stations have less detailed accounts than those in Maryland.

Potomac	
STATION	01646500 POTOMAC RIVER NEAR WASHINGTON, DC
LOCATION	Lat 38°56'59.2", long 77°07'39.5", Montgomery County, Hydrologic Unit 02070008, on left bank just upstream from Little Falls Dam, 1 mi upstream from District of Columbia boundary line, 1.2 miles upstream from Chain Bridge, 1.8 miles east of Langley, Fairfax County, and at mile 117.4
DRAINAGE AREA	11,560 square miles
PERIOD OF RECORD	March 1930 to current year
GAGE	Water-stage recorder and concrete control. Datum of gage is 37.95 ft above sea level. Prior to June 7, 1930, non-recording gage, and June 7, 1930, to Jan. 22, 1965, water-stage recorder at site 1 miles upstream on right bank at same datum
REMARKS	Diversions at Great Falls through aqueducts, and since June 1959, from gage pool at Little Falls Dam, for municipal supply of Washington, D.C.; since October 1958, at Rockville Filtration Plant, for municipal supply of city of Rockville; since April 1961, at Potomac Filtration Plant for water supply of Washington Suburban Sanitary District; since October 1961, at Fairfax Water Treatment Plant for water supply of city of Fairfax (from Goose Creek); since April 1964, at Violets Lock to Chesapeake and Ohio Canal; and since October 1985, at Fairfax County Water Authority Treatment Plant for water supply of the

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	county. Low flow affected slightly prior to July 1981 by Stony River Reservoir, since December 1950, by Savage River Reservoir and since July 1981, by Jennings Randolph Lake. National Weather Service gage-height telemeter at station. U.S. Geological Survey satellite collection platform at station
EXTREMES FOR PERIOD OF RECORD	Maximum discharge, 484,000 $feet^3 \cdot s^{-1}$, Mar. 19, 1936, gage height, 28.1 ft, site then in use; minimum daily discharge observed at gaging station, 121 $feet^3 \cdot s^{-1}$, Sept. 9, 1966, does not include diversion of 489 $feet^3 \cdot s^{-1}$ for municipal use; minimum daily discharge (adjusted), 601 $feet^3 \cdot s^{-1}$, Sept. 10, 1966, includes diversion of 449 $feet^3 \cdot s^{-1}$ for municipal use
Susquehanna	
STATION	01578310 SUSQUEHANNA RIVER AT CONOWINGO, MD
LOCATION	Lat 39°39'28.1", long 76°10'28.2", Harford County, Hydrologic Unit 02050306, at downstream side of Conowingo Dam, 1.0 miles southwest of Conowingo, and 9.9 miles upstream from mouth
DRAINAGE AREA	27,100 square miles
PERIOD OF RECORD	October 1967 to current year
GAGE	Water-stage recorder. Datum of gage is 5.00 feet above sea level
EXTREMES FOR PERIOD OF RECORD	Maximum discharge, 1,130,000 $feet^3 \cdot s^{-1}$, June 24, 1972, gage height, 36.83 feet; minimum discharge, 144 $feet^3 \cdot s^{-1}$, Mar. 2, 1969

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Choptank	
STATION	01491000 CHOPTANK RIVER NEAR GREENSBORO, MD
LOCATION	Lat 38°59'49.9", long 75°47'08.9", Caroline County, Hydrologic Unit 02060005, on left bank at highway bridge, 0.1 miles upstream from Gravelly Branch, 2.0 miles northeast of Greensboro, and 60 miles upstream from mouth.
DRAINAGE AREA	113 square miles
PERIOD OF RECORD	January 1948 to current year
GAGE	Water-stage recorder and concrete control. Datum of gage is 3.51 feet above sea level
EXTREMES FOR PERIOD OF RECORD	Maximum discharge, 6,970 $feet^3 \cdot s^{-1}$, Aug. 4, 1967, gage height, 14.47 feet; minimum discharge, 1.2 $feet^3 \cdot s^{-1}$, Aug. 29, 1966 & Sept. 3, 1987
Patuxent	
STATION	01594440 PATUXENT RIVER NEAR BOWIE, MD
LOCATION	Lat 38°57'21.3", long 76°41'37.3" Anne Arundel County, Hydrologic Unit 02060006, on left bank 45 feet upstream from bridge on U.S. Highway 50 (John Hanson Highway), 3.0 miles east of Bowie City Hall, 3.1 miles downstream from mouth of Little Patuxent River, 4.2 miles northwest of Davidsonville, and 60 miles upstream from mouth

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DRAINAGE AREA	348 square miles
PERIOD OF RECORD	April 1955 to June 1977 (gage heights and discharge measurements only), June 1977 to current year
GAGE	Water-stage recorder and crest-stage gage. Datum of gage is 13.10 feet above sea level. Prior to June 27, 1977, non-recording gage at same site and datum
EXTREMES FOR PERIOD OF RECORD	Maximum discharge, 31,100 $feet^3 \cdot s^{-1}$, June 22, 1972, gage height, 27.90 feet; minimum discharge, 32 $feet^3 \cdot s^{-1}$, Aug. 9, 1966
Nanticoke	
STATION	01487000 NANTICOKE RIVER NEAR BRIDGEVILLE, DE
LOCATION	Lat 38°43'42.0", long 75°33'42.7", Sussex County, Hydrologic Unit 02060008, on left bank at downstream side of highway bridge, 800 ft downstream from Gum Branch, 2.5 miles southeast of Bridgeville, and 50.5 miles upstream from mouth
DRAINAGE AREA	75.4 square miles
PERIOD OF RECORD	April 1943 to current year. Prior to October 1955, published as Gravelly Fork near Bridgeville
GAGE	Water-stage recorder. Datum of gage is 13.64 feet above sea level (levels by Soil Conservation Service). Prior to Apr. 19, 1947, non-recording gage, and Apr. 19, 1947 to Dec. 18, 1969, recording gage at present site and datum. Timber control Sept. 3, 1947 to Dec. 18, 1969. Feb. 18, 1970 to Oct. 1, 1973, recording gage at site 300 feet downstream at same datum

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EXTREMES FOR PERIOD OF RECORD	Maximum discharge, 3,020 $feet^3 \cdot s^{-1}$, Feb. 26, 1979, gage height, 10.31 feet; minimum discharge, 6.3 $feet^3 \cdot s^{-1}$, Sept. 29, 1943
Rappahannock	
LOCATION	Latitude 38°18'30", Longitude 77°31'46" NAD27, Spotsylvania County, Virginia, Hydrologic Unit 02080104
DRAINAGE AREA	1,596.00 square miles
STATION DATA	Peak stream flow 908-01-13 2002-04-23. Daily stream flow 1907-09-19 2002-09-30
York (Mattaponi branch)	
LOCATION	Latitude 37°53'16", Longitude 77°09'48" NAD27, King William County, Virginia , Hydrologic Unit 02080105
DRAINAGE AREA	601.00 square miles
GAGE	Datum of gage is 12.43 feet above sea level NGVD29
STATION DATA	Peak stream flow 1889-06-00 2002-05-02. Daily stream flow 1941-09-19 2002-09-30
York (Pamunkey branch)	
LOCATION	Latitude 37°46'03", Longitude 77°19'57" NAD27, Hanover County, Virginia,

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	Hydrologic Unit 02080106
DRAINAGE AREA	1,081.00 square miles
GAGE	Datum of gage is 14.72 feet above sea level NGVD29
STATION DATA	Peak stream flow 1928-08-00 2002-08-30. Daily stream flow 1941-10-01 2002-09-30
James	
LOCATION	Latitude 37°33'47", Longitude 77°32'50" NAD27, Henrico County, Virginia, Hydrologic Unit 02080205
DRAINAGE AREA	6,758.00 square miles
GAGE	Datum of gage is 98.82 feet above sea level NGVD29
STATION DATA	Peak stream flow 1935-09-07 2002-04-24. Daily stream flow 1934-10-01 2002-09-3

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13. List of figures

13.1. Chesapeake Bay

13.2. Foraging arena

13.3. Food web components

13.4. Ecoranger

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13.5. Mixed trophic impacts

Figure 5. Mixed trophic impact analysis for the 1950-ecosystem model; showing direct and indirect impact through the food web. Impacting groups are shown in rows, impacted in columns. Positive impacts are shown above the baselines, negative below. Impacts are relative but comparable between groups. Only some selected groups are shown.

13.6. Time series fit, biomass

Figure 6. Time series fit for biomasses in the 1950-ecosystem model. Time series from assessments or surveys are shown as dots while Ecosim simulation results are indicated with lines. The time period (X-axis) is 1950-2002 for all plots.

13.7. Time series fit, catches

Figure 7. Time series fit for catches in the 1950-ecosystem model. Catch time series are shown as dots, while the catches predicted by Ecosim (from biomasses and fishing mortalities) are shown as lines. The time period (X-axis) is 1950-2002 for all plots. Where a simulation matches the catches for all years, it indicates that the catches were used to estimate fishing mortalities for the Ecosim run.

13.8. Nutrient loading

Figure 8. Nutrient loading for the Chesapeake Bay, 1950-2002 as estimated from a two-layer hydrodynamic/climatic model. Indications are that the nutrient loading has

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been reduced with 0.3% per year over the period – the linear trend line only serves to illustrate this estimate, the actual monthly patterns were used to drive the fitted Ecosim scenario.

13.9. Advection fields

Figure 9. Chesapeake Ecosystem Model with Advection Fields dialogue box showing advection fields for January.

13.10. Bathymetry map

Figure 10. Chesapeake bathymetry map edited including addition of a 'channel' to the ocean.

13.11. Depth comparisons

Figure 11. Histogram of area in km^2 at one meter depth intervals for the original bathymetry, 1000 m and 2000 m edited grids.

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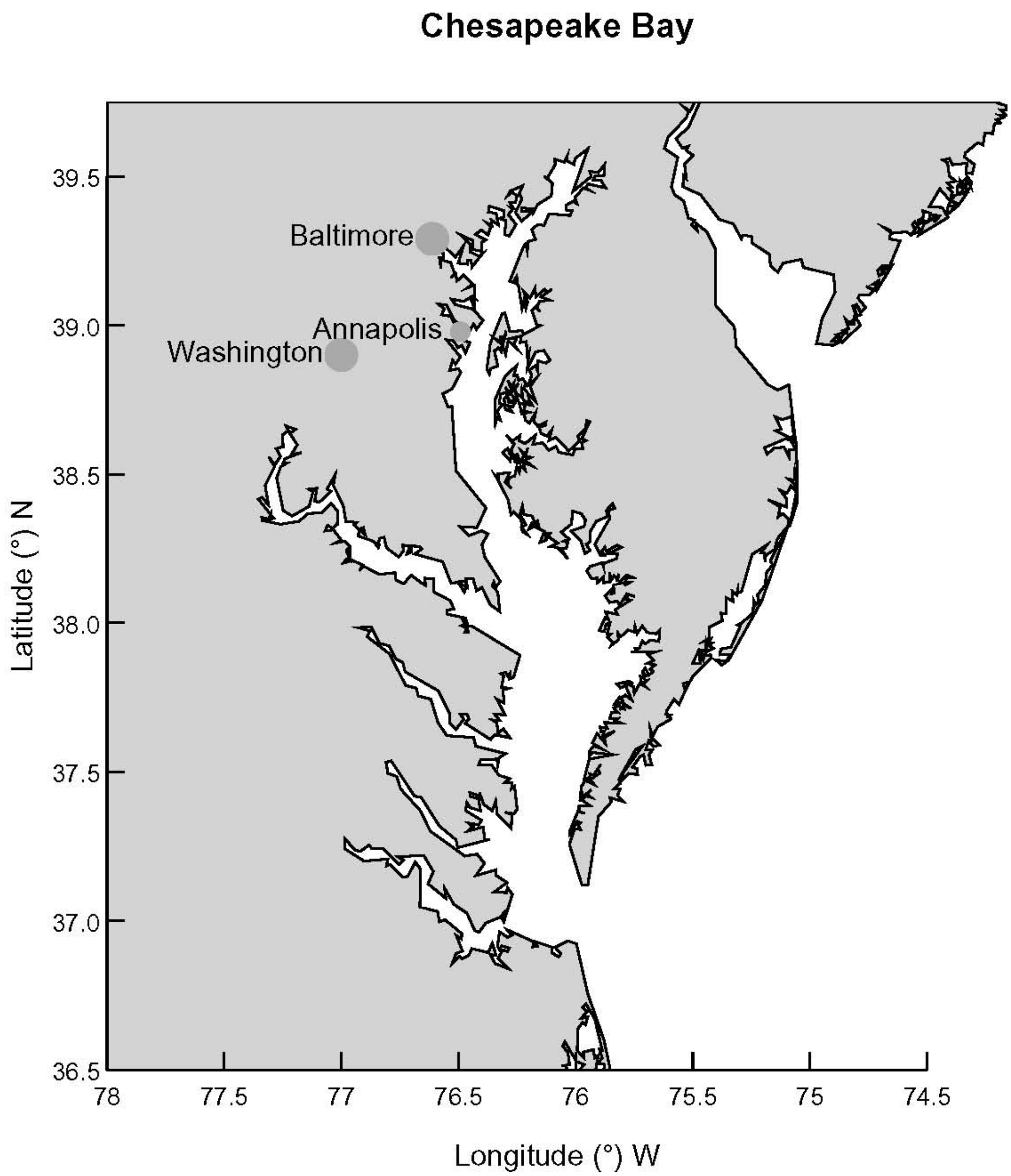
Figure 1


Chesapeake Bay
Baltimore
Annapolis
Washington
39.5
39.0
38.5
38.0
37.5
37.0
36.5
Latitude (°) N
78
77.5
77
76.5
76
75.5
75
74.5
Longitude (°) W

Do

Figure 2

a_{ij} = search rate of predator
B_i = total prey biomass
B_j = predator biomass
v = behavioral exchange rate
V_i = vulnerable prey biomass

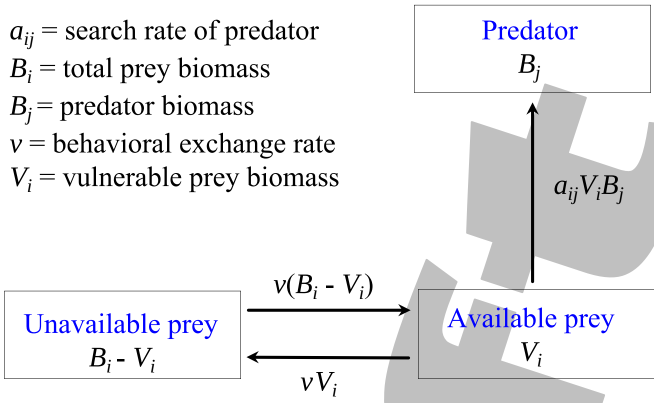


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FIGURE 3

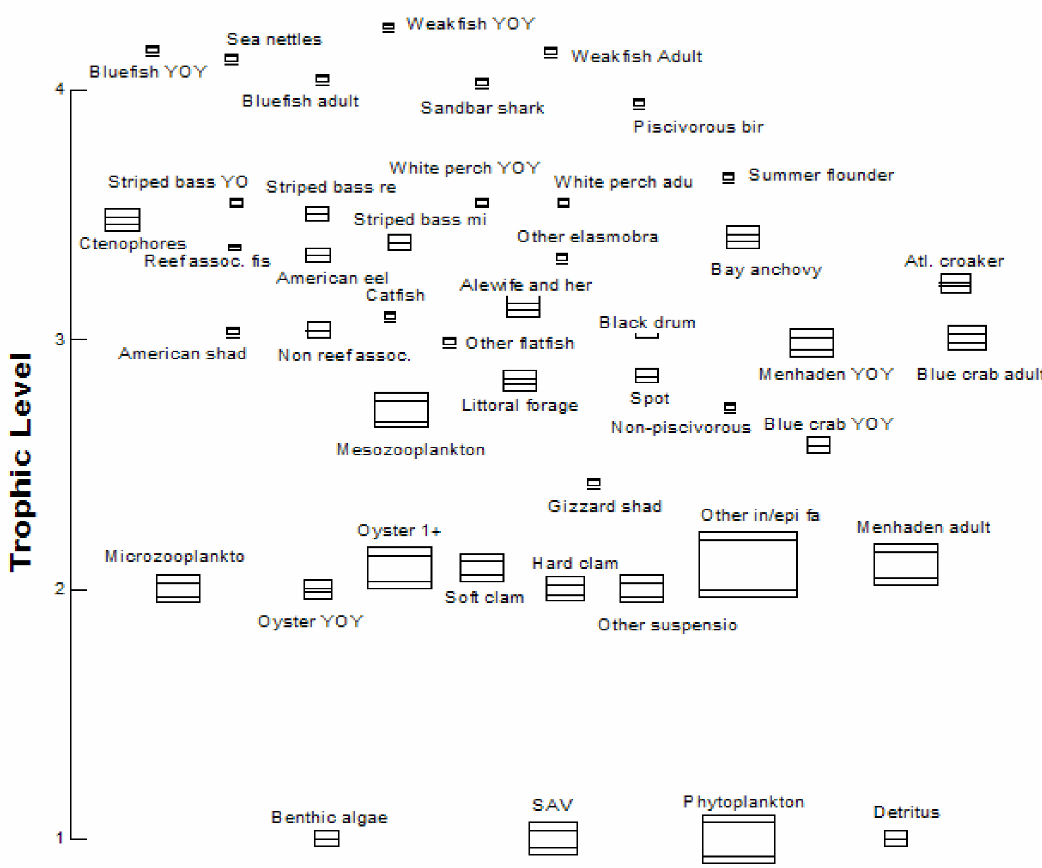

FIGURE 4

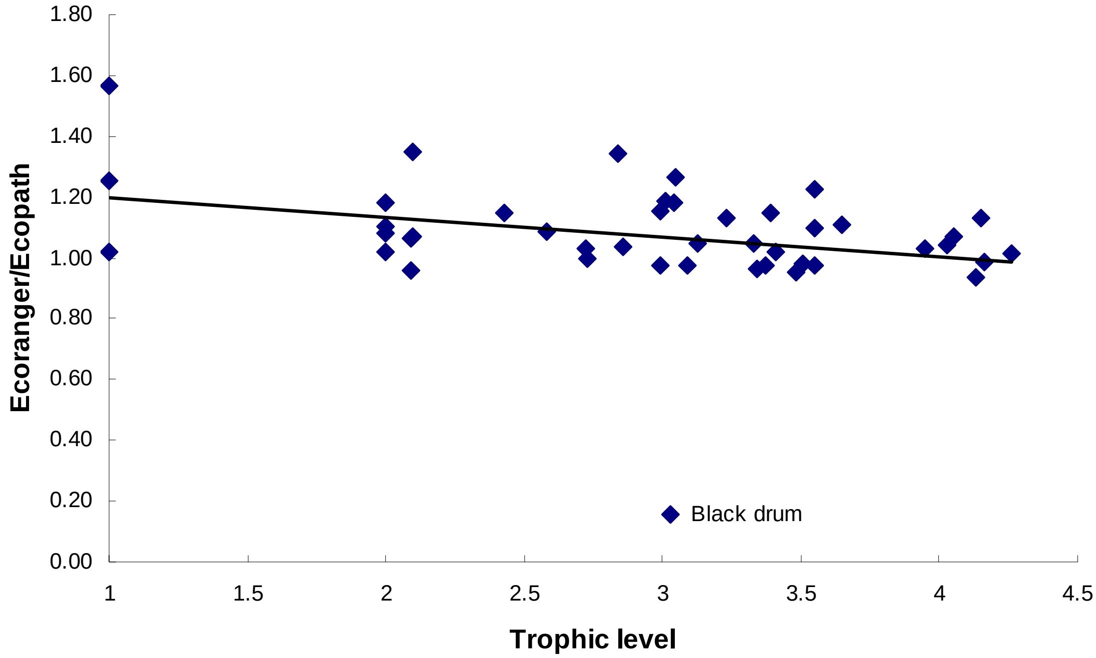

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FIGURE 5

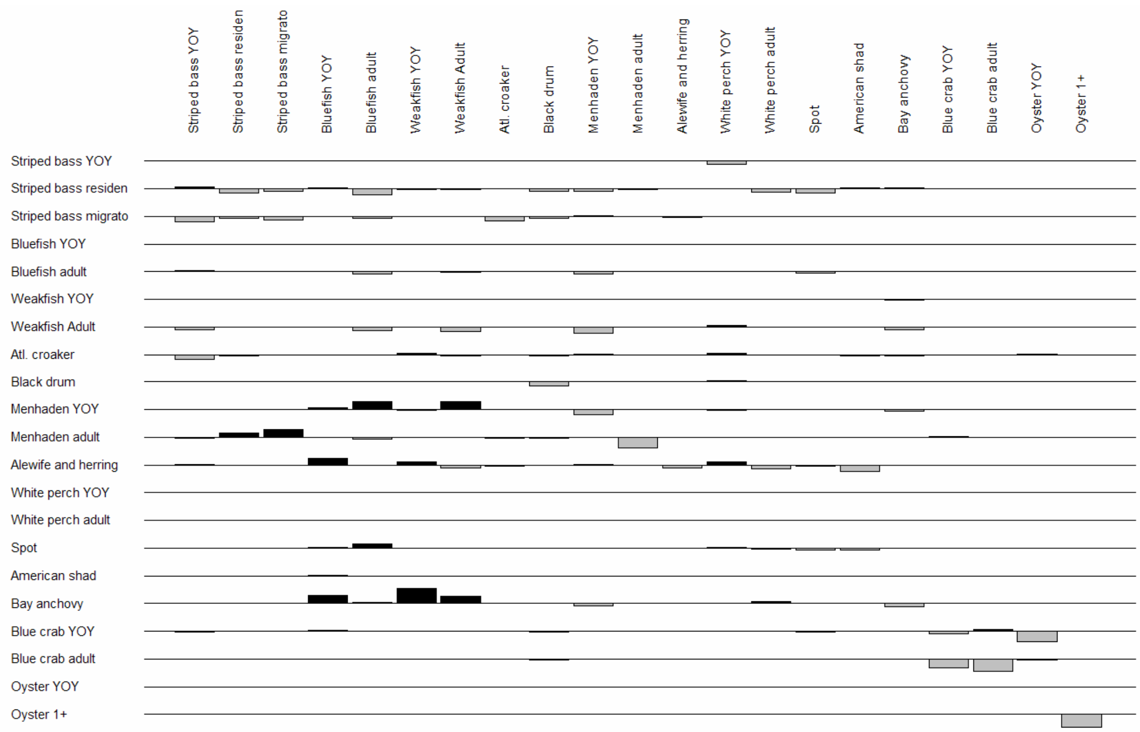

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FIGURE 6

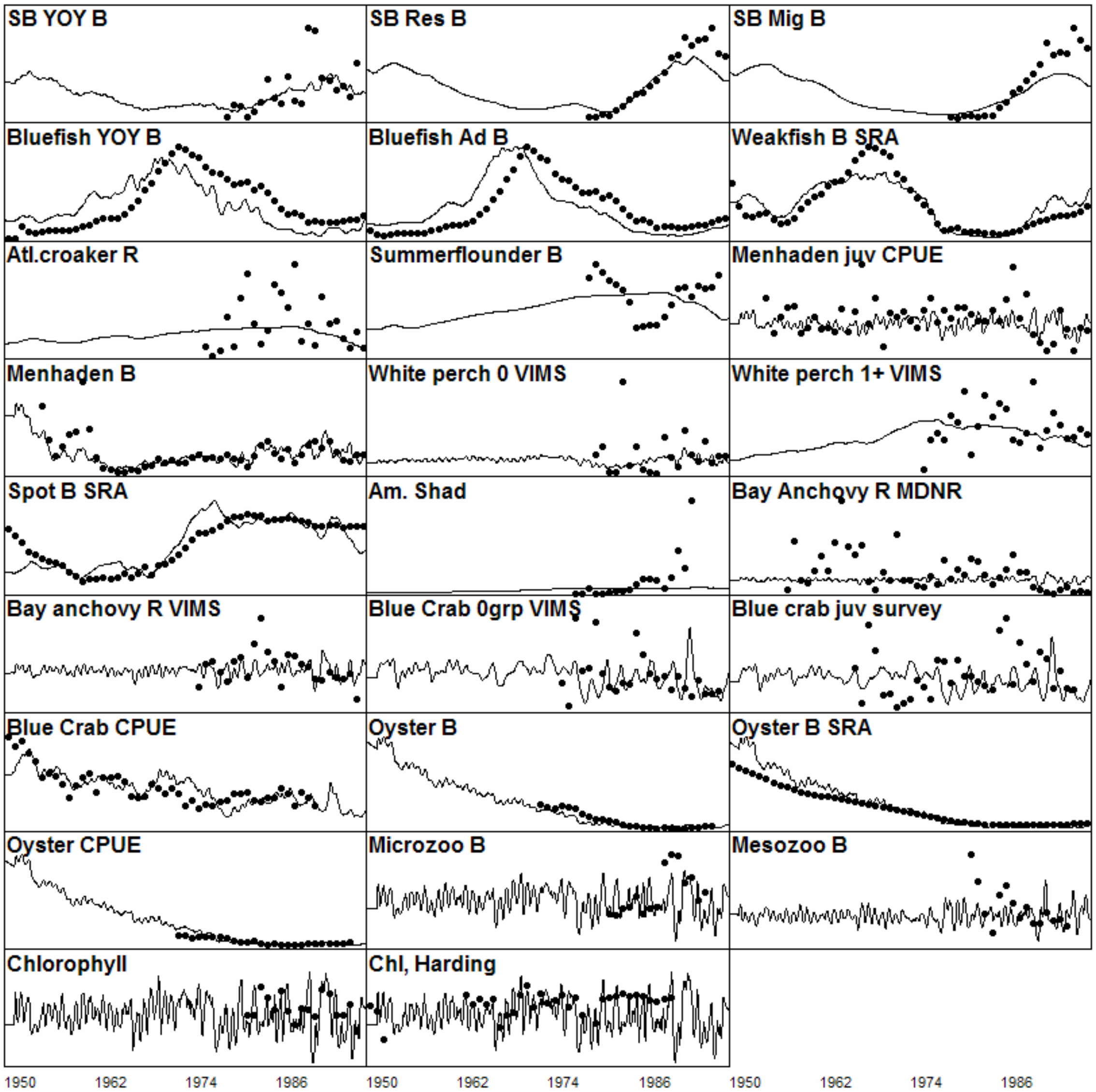
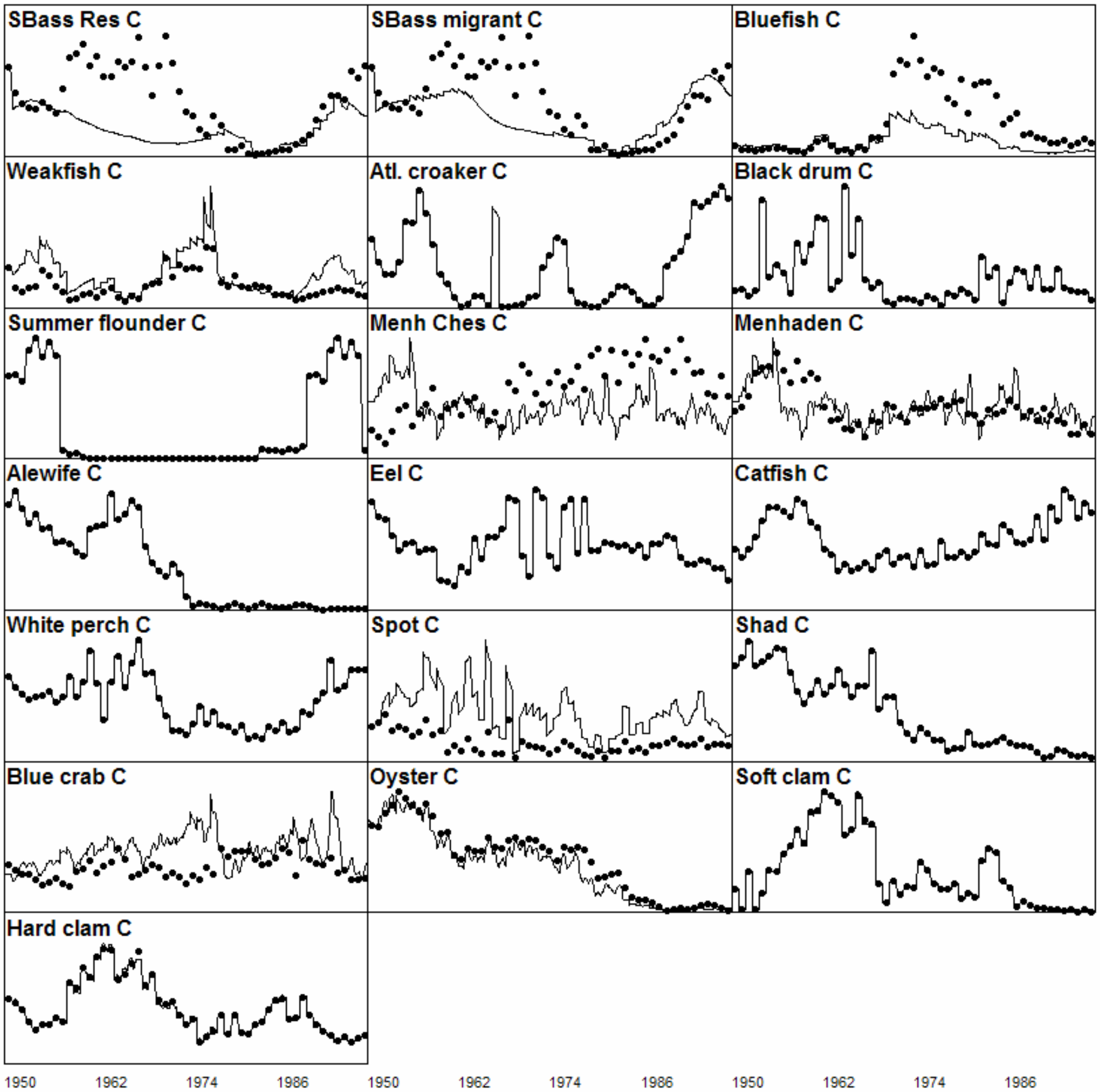
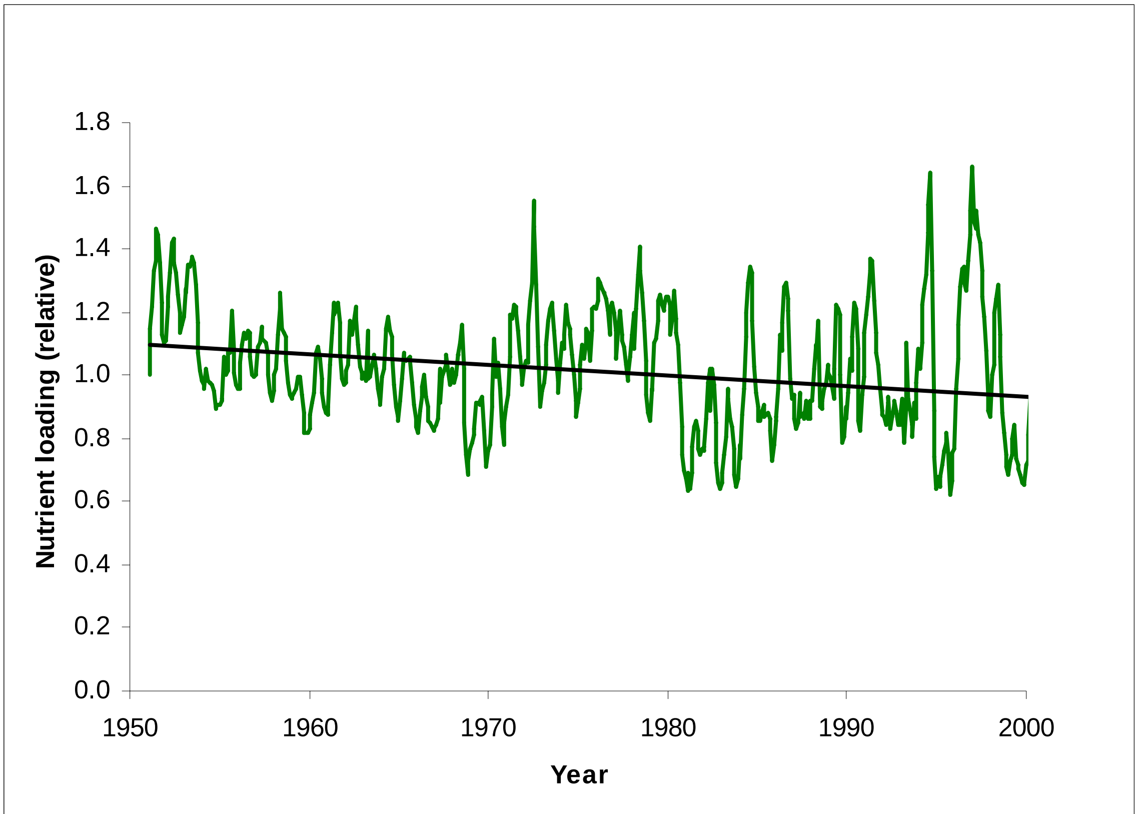

SB YOY B
SB Res B
SB Mig B
Bluefish YOY B
Bluefish Ad B
Weakfish B SRA
Atl.croaker R
Summerflounder B
Menhaden juv CPUE
Menhaden B
White perch 0 VIMS
White perch 1+ VIMS
Spot B SRA
Am. Shad
Bay Anchovy R MDNR
Bay anchovy R VIMS
Blue Crab 0grp VIMS
Blue crab juv survey
Blue Crab CPUE
Oyster B
Oyster B SRA
Oyster CPUE
Microzoo B
Mesozoo B
Chlorophyll
Chl, Harding
1950
1962
1974
1986
1950
1962
1974
1986
1950
1962
1974
1986

FIGURE 7.


SBass Res C
SBass migrant C
Bluefish C
Weakfish C
Atl. croaker C
Black drum C
Summer flounder C
Menh Ches C
Menhaden C
Alewife C
Eel C
Catfish C
White perch C
Spot C
Shad C
Blue crab C
Oyster C
Soft clam C
Hard clam C
1950
1962
1974
1986
1950
1962
1974
1986
1950
1962
1974
1986

Do N

FIGURE 8



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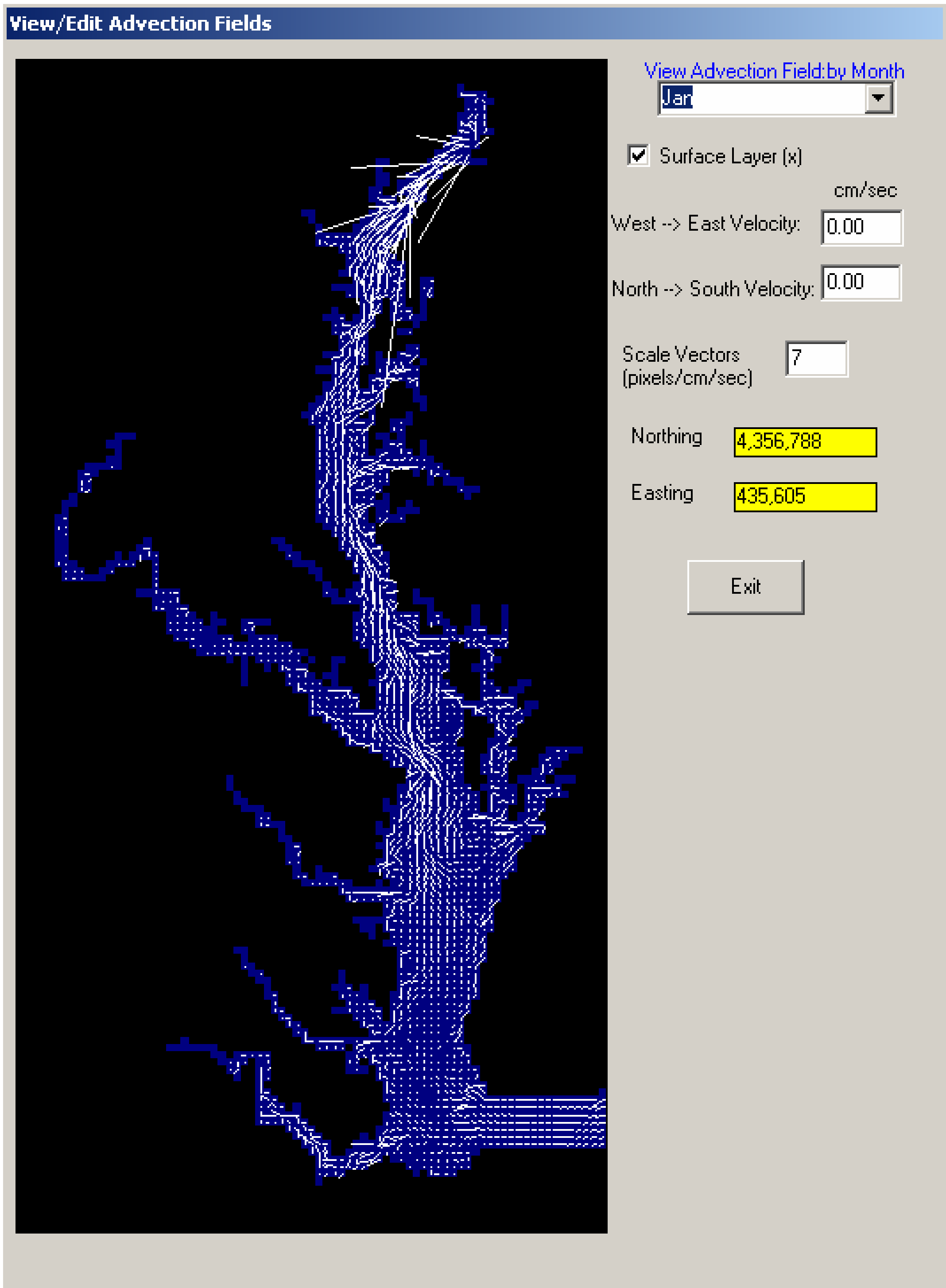

View/Edit Advection Fields
View Advection Field:by Month
Jan
Surface Layer (x)
cm/sec
West --> East Velocity:
0.00
North --> South Velocity:
0.00
Scale Vectors
(pixels/cm/sec)
7
Northing
4,356,788
Easting
435,605
Exit

FIGURE 9

Do

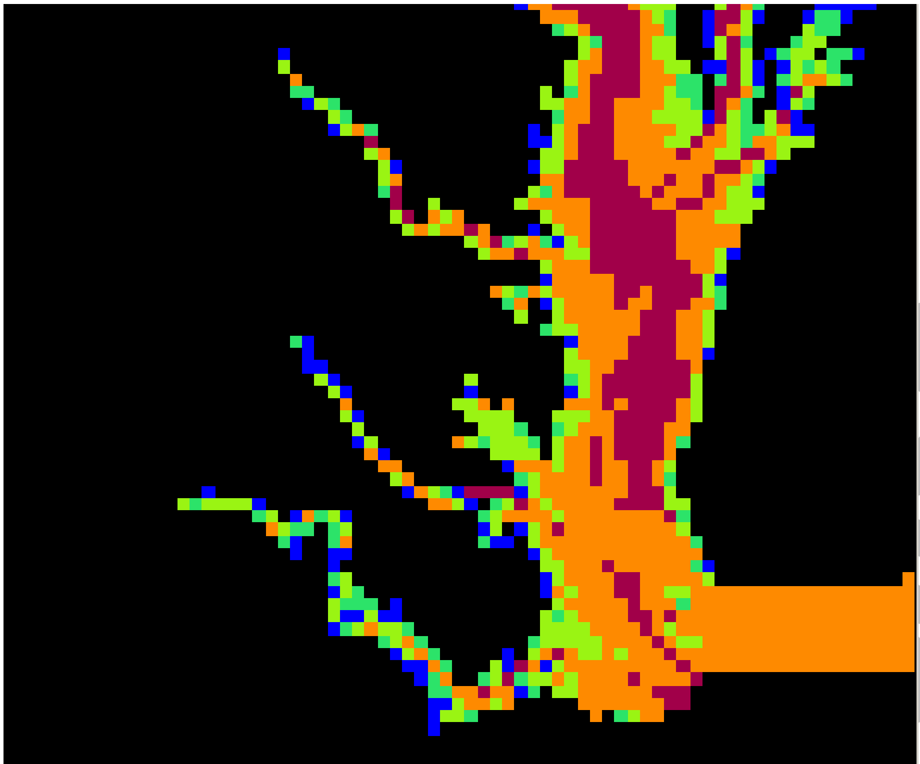
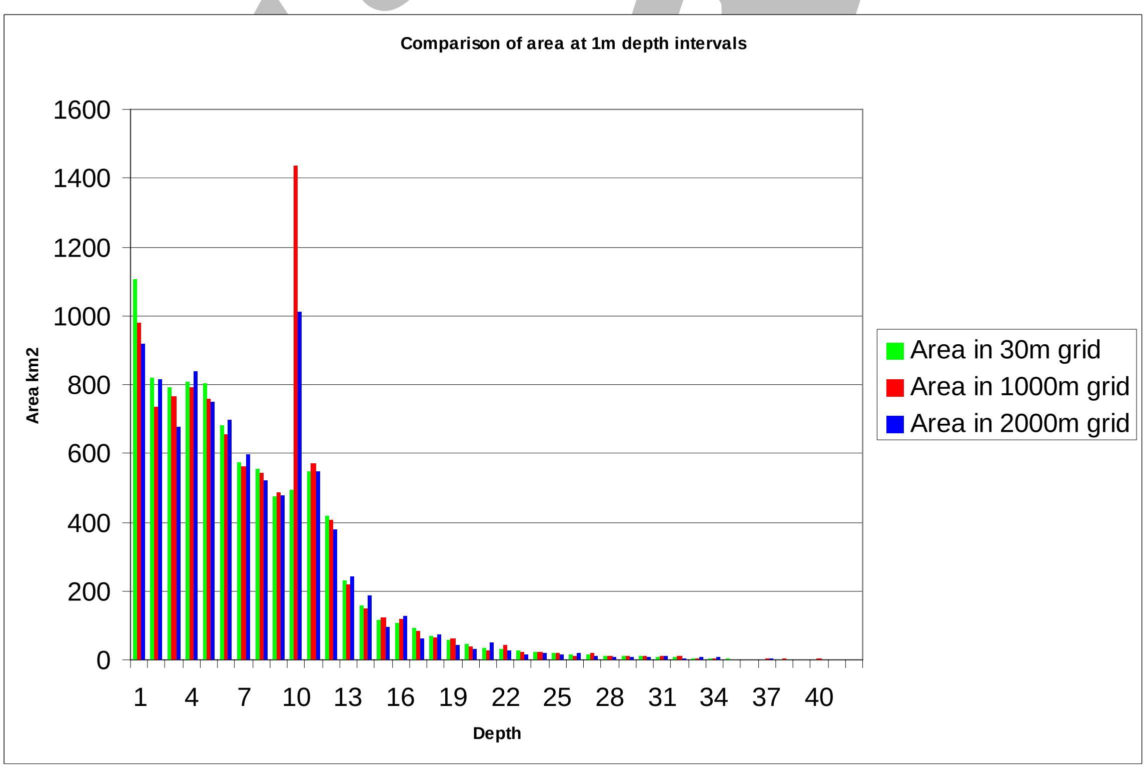


FIGURE 10



Comparison of area at 1m depth intervals
Area km2
1600
1400
1200
1000
800
600
400
200
0
1
4
7
10
13
16
19
22
25
28
31
34
37
40
Depth
Area in 30m grid
Area in 1000m grid
Area in 2000m grid

FIGURE 11.

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